National Library of Canada

Acquisitions and Bibliographic Services Branch

395 Wellington Street
Ottawa, Ontario
K1A 0N4

Bibliothèque nationale du Canada

Direction des acquisitions et des services bibliographiques

395, rue Wellington
Ottawa (Ontario)
K1A 0N4

Your file Votre référence

Our file Notre référence

NOTICE

The quality of this microform is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us an inferior photocopy.

Reproduction in full or in part of this microform is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30, and subsequent amendments.

AVIS

La qualité de cette microforme dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de qualité inférieure.

La reproduction, même partielle, de cette microforme est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30, et ses amendements subséquents.

Canada

UNIVERSITY OF ALBERTA

Co-activation Patterns of Jaw Muscles in Normal and Orofacial Pain Subjects

BY

Jian Mao ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfilment of the requirements for the degree of Doctor of Philosophy

IN

Oral Biology
Faculty of Dentistry

Edmonton, Alberta, CANADA
Fall, 1992

National Library
of Canada

Acquisitions and
Bibliographic Services Branch

395 Wellington Street
Ottawa, Ontario
K1A 0N4

Bibliothèque nationale
du Canada

Direction des acquisitions et
des services bibliographiques

395, rue Wellington
Ottawa (Ontario)
K1A 0N4

Your file Votre référence

Our file Notre référence

The author has granted an irrevocable non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of his/her thesis by any means and in any form or format, making this thesis available to interested persons.

L'auteur a accordé une licence irrévocable et non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de sa thèse de quelque manière et sous quelque forme que ce soit pour mettre des exemplaires de cette thèse à la disposition des personnes intéressées.

The author retains ownership of the copyright in his/her thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without his/her permission.

L'auteur conserve la propriété du droit d'auteur qui protège sa thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

ISBN 0-315-77414-2

Canadä

UNIVERSITY OF ALBERTA

RELEASE FORM

NAME OF AUTHOR: Jian Mao

TITLE OF THESIS: Co-activation Patterns of Jaw Muscles in Normal and Orofacial Pain Subjects.

DEGREE: Doctor of Philosophy

YEAR THIS DEGREE GRANTED: 1992

Permission is hereby granted to the University of Alberta Library to reproduce single copies of this thesis and to lend or sell such copies for private, scholarly or scientific research purposes only.

The author reserves all other publication and other rights in association with the copyright in the thesis, and except as hereinbefore provided neither the thesis nor any substantial portion thereof may be printed or otherwise reproduced in any material form whatever without the author's prior written permission.

#304 10426 84 Avenue
Edmonton, Alberta, CANADA
T6E 2H2

Date: September 9, 1992

QUOTE PAGE

Skeletal muscles and the motoneurons that control them are the products of evolution. Survival placed a premium on speed of movement to capture prey or escape predators, on the capacity to resist fatigue, on a favorable ratio between the weight and strength of muscle, and perhaps above all, on efficient use of energy.

--------- Elwood Henneman (1980)

UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled Co-activation Patterns of Jaw Muscles in Normal and Orofacial Pain Subjects submitted by **Jian Mao** in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

Jeffrey W. Osborn (Supervisor)

Baragar

F. Alvin Baragar (Thesis committee member)

Donald G. Bellow

Donald G. Bellow (Thesis committee member)

Paul W. Major (Thesis committee member)

RBStein

Richard B. Stein (Thesis committee member)

Susan W. Herring
(External Examiner, University of Washington)

Date: 3 Sept. 92

TO

Susan, for her patience and support.

My parents, for their understanding.

ABSTRACT

A 2 *mm* thick, custom-developed, force transducer was used to specify the direction and magnitude, in three dimensions, of bite force tasks (as visual feedback) for measuring the activity of masseter and temporalis in normal and temporomandibular joint disorder (TMD) subjects. The directions were vertical and 20° forward, backward, medial, and lateral from the vertical at 90° intervals in the horizontal plane; the magnitudes being 50 *Newton* to 300 *N* in 50 *N* increments between occluding first molars. Left and right side muscle tensions were measured as the normalized surface electromyographic (EMG) activity. Five normal subjects (three of whom were tested separately on both sides of the jaw) were studied. Major results were 1) linear regression analyses showed a positive correlation ($r = 0.87 \pm 0.17$; mean±standard deviation) between the surface EMGs of bilateral masseter and temporal muscles and the incremental bite forces in the tested directions; 2) muscle patterns showed mirror image for the equivalent tasks performed on the left and right sides; 3) muscle patterns were roughly constant provided that the bite force directions were fixed; and 4) one-way *ANOVA* and the Bonferroni test showed that the mean EMG ratios of the paired (above) muscles were significantly different and were distinctive for most bite force directions ($p < 0.001$ in most cases). Six TMD patients with jaw muscle pain/tenderness were then tested using the normal muscle patterns as control. It was found that 1) there were some deviated muscle patterns and 2) some of the unusual muscle patterns seemed to be related to clinical findings. The most important conclusions were as follows. (1) The integrated EMG activity of masseter and temporal muscles are approximately linear with the graded bite forces exerted by all the jaw closing muscles as a synergistic group in the studied directions. (2) The left and right side muscle activity is equivalent. (3) For each bite force direction, there is a specific pattern of jaw closing muscle activity regardless of the bite force magnitude. (4) Normal muscle patterns may be useful in detecting aberrant activity in TMD patients. (5) The direction of a mechanical force exerted by a group of synergistic muscles might be as importantly controlled as its magnitude.

ACKNOWLEDGEMENTS

I sincerely thank Dr. JW Osborn, my supervisor, for his stimulating thoughts. His encouragement and friendship have provided me with what I need for such a challenging program. I thoroughly enjoyed discussing with him as much about science as about Beethoven's work. Dr. Osborn's enthusiasm and achievement in research would last as a role model for the rest of my career.

Each member of my thesis committee has contributed enormously to this inter-disciplinary project.

My special thanks go to Dr. RB Stein who aroused my interests in the neural control of movements. I greatly benefited from his knowledge and advice over numerous meetings and correspondence. His encouragement has been invaluable and his influence is profound.

Dr. PW Major kindly offered to update my clinical skill in the TMJ clinic. His expertise in this area was extremely important for me to complete the clinical component of my project.

I would like to express my gratefulness to Dr. FA Baragar who taught me a working knowledge of linear programming and elementary computer jaw modelling. Dr. Baragar also provided numerous suggestions useful to this project.

I am greatly indebted to Dr. DG Bellow who patiently led me into strain and stress measurements and provided critical suggestions about force measurements.

I also extend my sincere thank to Dr. SW Herring, who served as the external examiner, for her sharp and valuable evaluation of my thesis.

In this faculty, Dr. PG Scott, who served as chairman and examiner for my defense, has provided many valuable suggestions during my training; Drs. GH Sperber, KE Glover, JA Hargreaves and JI Woronuk read the thesis and made valuable comments and suggestions.

I am grateful to the entire staff in the Department of Oral Biology, headed successively by Dr. JW Osborn and Dr. DM Paton, for their concern and friendship shown to me during my graduate training. Dr. Paton kindly provided seed fund for this project. I also greatly appreciate that both Dr. Paton and Dr. NK Wood, Dean of the Faculty, showed strong support for me to establish my career. I also thank the entire staff in the TMJ clinic for sharing research interests and providing a friendly working atmosphere.

My thanks go to the following people for their assistance: Mr. Brian Cielin, who taught me the art of strain gauge installation and provided me with facilities; Mr. Larry McMurdo, who provided many contributions regarding electronics; and Ms. Betty Skrypichayko, who excellently managed the appointment of my TMJ subjects.

My warmest thanks go to all my friends for their encouragement. Among them, Jeff Westley, a computer guru, freely shared his knowledge on both hardware and software.

I also thank all the volunteers and patients for participating my studies.

I own much to Susan for her support during my studies. We have shared a common interest in neuroscience. I emphasize that my parents, as academics themselves, have shown understanding over the Pacific.

Table of Contents

CHAPTER

1. INTRODUCTION...1

1.I...Statement of the problems...2
1.II...Objectives...8

2. REVIEW OF THE LITERATURE...10

2.I...BITE FORCE AND BITE FORCE TRANSDUCER...12

2.I.1...Bite force...13
  .a...Maximum voluntary bite force...14
    .(1)...Magnitude...14
    .(2)...Correlations...16
  .b...Direction of the bite force...22
2.I.2...Bite force transducer...24
  .a...Uni-directional transducers...26
  .b...Multi-directional transducer...28

2.II...MUSCLES OF MASTICATION...32

2.II.1...EMG of jaw muscles during dynamic tasks...33
  .a...Chewing cycle...33
  .b...Mastication...34
  .c...Jaw movement...36
2.II.2...EMG of jaw muscles during static tasks...37
  .a...Isometric tasks: unknown direction of bite force...37
    .(1)...Intercuspal clenching...38
    .(2)...Changing muscle length...39
    .(3)...Distribution of tensions among jaw muscles...43
    .(4)...Linearity...45
  .b...EMG correlated with the direction of bite force...48
    .(1)...MacDonald and Hannam (1984*a* and 1984*b*)...49
    .(2)...van Eijden and coworkers (1988*a* - 1991)...49

2.III...ABNORMAL JAW MUSCLES: BITE FORCE AND EMG...52

2.III.1...The silent period...54
2.III.2...Resting jaw muscles and hyperactivity...56
2.III.3...Maximum effort and length-tension relation...59
2.III.4...Muscle activity patterns during jaw movement...60
2.III.5...Effects of occlusal splint on muscle activity...62
  .a...Maximum inter-cuspal clenching...63
  .b...Postural and nocturnal muscle activity...65
2.III.6...Mandibular dyskinesia...67

3. MATERIAL AND METHODS...70

3.I...DEVELOPMENT AND USE OF THE FORCE TRANSDUCER...71

3.I.1...The housing...72
3.I.2...The sensors...74
3.I.3...Strain gauge conditioning...75
3.I.4...The calibration...76
3.I.5...Visual feedback...78
3.I.6...The use...80
3.I.7...Tasks...81

3.II...ELECTROMYOGRAPHY, DATA ANALYSIS AND SUBJECTS...83

3.II.1...Architecture of the muscles under study...84
3.II.2...Surface EMG apparatuses...86
3.II.3...Data analysis and statistics...87
3.II.4...Selection and clinical examination of subjects...89
    .a...Normal subjects...90
    .b...TMD subjects...91

4. RESULTS...92

4.I...CO-ACTIVATION PATTERNS OF NORMAL JAW MUSCLES...93

4.I.1...Production of the bite force tasks...94
4.I.2...Dispersion of the EMG data...95
4.I.3...Bite force-EMG relationship...96
4.I.4...Mirror image muscle patterns for left and right tasks...98
4.I.5...Muscle tensions with regard to bite force directions...100
    .a...Tensions as groups...100
    .b...Individual muscle tensions...102
        .(1)...In the sagittal plane...102
        .(2)...In the frontal plane...103
4.I.6...Ratios of muscle pairs...103
    .a...Sagittal plane: ratios for force directions...104
    .b...Frontal plane: ratios for force directions...105
    .c...The ratios for force directions in 3-D...106

4.II...BEHAVIOR OF JAW MUSCLES OF TMD SUBJECTS...107

4.II.1...Case I...108
    .a...Clinical examination...109
    .b...EMG muscle patterns...109
4.II.2...Case II...111
    .a...Clinical examination...111
    .b...EMG muscle patterns...111

- 4.II.3...Case III...113
  - .a...Clinical examination...113
  - .b...EMG muscle patterns...114
- 4.II.4...Case IV...115
  - .a...Clinical examination...116
  - .b...EMG muscle patterns...116
- 4.II.5...Case V...118
  - .a...Clinical examination...118
  - .b...EMG muscle patterns...118
- 4.II.6...Case VI...119
  - .a...Clinical examination...119
  - .b...EMG muscle patterns...119

5. DISCUSSION AND CONCLUSIONS...121

- 5.I...DISCUSSION...122

- 5.I.1...The bite force transducer...123
- 5.I.2...Direction of a resultant force of synergistic muscles...126
  - .a...Direction as a motor control variable...128
  - .b...Direction of a bite force...129
    - .(1)...Chewing force...129
    - .(2)...Submaximal isometric bite force...130
    - .(3)...Maximum voluntary bite force...131
- 5.I.3...Comparing with van Eijden *et al.* (1990)...133
- 5.I.4...Relation between bite force and surface EMG...136
- 5.I.5...Symmetry of muscle patterns...139
- 5.I.6...Co-activation of synergistic muscles...141
- 5.I.7...Recruitment patterns of jaw muscles...144
- 5.I.8...Muscle partitioning...146
- 5.I.9...Normal jaw muscle activity patterns...148
  - .a...Inter-muscle patterns...148
  - .b...Individual muscle patterns...149
- 5.I.10...Muscle activity patterns of TMD subjects...150
  - .a...Unilateral pain cases...151
    - .(1)...Case I...151
    - .(2)...Case II...152
    - .(3)...Case V...153
    - .(4)...Case VI...154
  - .b...Complex pain cases...155
    - .(1)...Case III...155
    - .(2)...Case IV...156
  - .c...Summary...158

- 5.II...CONCLUSIONS...160

TABLES...163

FIGURES AND CAPTIONS...169

BIBLIOGRAPHY...250

APPENDICES...277

LIST OF TABLES

Table 1...Maximum incisal bite force...163
Table 2...Maximum bite force on premolars...164
Table 3...Maximum bite force on molars...165
Table 4...Effects of local anesthesia on MVBF...166
Table 5...Accuracy of the force transducers during calibration...167
Table 6...Correlation coefficients (*r* values): means and standard deviations...168

LIST OF FIGURES

Figure 1....Housing of the bite force transducer housing...170

Figure 2....The bite force transducer: housing and sensors...172

Figure 3....The bite force transducer: parts of the housing...174

Figure 4....Dimensions of the transducer...176

Figure 5....Single strain gauges as sensors...178

Figure 6....Wheatstone bridge: 1/4 bridge configuration...180

Figure 7....Force transducer calibration...182

Figure 8....Visual feedback of a bite force: magnitude and direction...184

Figure 9....Bite force transducer *in situ*: jaw separation...186

Figure 10...Flow diagram of bite force recording devices...188

Figure 11...Flow diagram of EMG recording devices...190

Figure 12...EMG signals: the raw, full-wave rectified and integrated...192

Figure 13...EMG signal-noise relation...194

Figure 14...Dispersion of EMG data...196

Figure 15...EMG activity: bite force directions in the sagittal plane...198

Figure 16...EMG activity: bite force directions in the frontal plane...200

Figure 17...*r* values for 20° forward bite forces...202

Figure 18...*r* values for 20° backward bite forces...204

Figure 19...*r* values for 20° lateral bite forces...206

Figure 20...*r* values for 20° medial bite forces...208

Figure 21...*r* values for vertical bite forces...210

Figure 22...Mirror image muscle patterns for left and right tasks...212

Figure 23...The averaged EMG data points for all bite force directions...214

Figure 24...Muscle tensions against bite directions in the sagittal plane...216

Figure 25...Muscle tensions against bite directions in the frontal plane...218

Figure 26...Ratios of muscle pairs in the sagittal plane...220

Figure 27...Ratios of muscle pairs in the frontal plane...222

Figure 28...Ratios of muscle pairs in the sagittal and frontal planes...224

Figure 29...Case I: the ratios of working temporalis over working masseter...225
Figure 30...Case I: the ratios of balancing temporalis over balancing masseter...226
Figure 31...Case I: the ratios of working temporalis over balancing temporalis...227
Figure 32...Case I: the ratios of working masseter over balancing masseter...228
Figure 33...Case II: the ratios of working temporalis over working masseter...229
Figure 34...Case II: the ratios of balancing temporalis over balancing masseter...230
Figure 35...Case II: the ratios of working temporalis over balancing temporalis...231
Figure 36...Case II: the ratios of working masseter over balancing masseter...232
Figure 37...Case III: the ratios of working temporalis over working masseter...233
Figure 38...Case III: the ratios of balancing temporalis over balancing masseter...234
Figure 39...Case III: the ratios of working temporalis over balancing temporalis...235
Figure 40...Case III: the ratios of working masseter over balancing masseter...236
Figure 41...Case IV: the ratios of working temporalis over working masseter...237
Figure 42...Case IV: the ratios of balancing temporalis over balancing masseter...238
Figure 43...Case IV: the ratios of working temporalis over balancing temporalis...239
Figure 44...Case IV: the ratios of working masseter over balancing masseter...240
Figure 45...Case V: the ratios of working temporalis over working masseter...241
Figure 46...Case V: the ratios of balancing temporalis over balancing masseter...242
Figure 47...Case V: the ratios of working temporalis over balancing temporalis...243
Figure 48...Case V: the ratios of working masseter over balancing masseter...244
Figure 49...Case VI: the ratios of working temporalis over working masseter...245
Figure 50...Case VI: the ratios of balancing temporalis over balancing masseter...246
Figure 51...Case VI: the ratios of working temporalis over balancing temporalis...247
Figure 52...Case VI: the ratios of working masseter over balancing masseter...248
Figure 53...Comparison with van Eijden *et al.* (1990)...249

LIST OF ABBREVIATIONS AND SYMBOLS

EMG...electromyography, electromyogram or electromyographic

EMG_{max}...maximum EMG (averaged from the top 200 MVC values)

GTO...Golgi tendon organ

kg...kilogram

M1...the first molar

M2...the second molar

ms...milliseconds

MVBF...maximum voluntary bite force

MVC...maximum voluntary contraction

N...Newton

PMR... periodontal mechano-receptor

TMD...temporomandibular disorders

TMJ...temporomandibular joint

type I fibers...slow-twitch muscle fibers; S fibers

type II fibers...fast-twitch muscle fibers

type IIA fibers...fast-twitch, fatigue-resistant; FR muscle fibers

type IIB...fatigue-susceptible; FF muscle fibers

LIST OF APPENDICES

#1...Pending patent through the Intellectual Property and Contracts Office of the University of Alberta...277

#2...Engineering Data Sheet for WK-06-060WR-350 rosette manufactured by Micro-Measurements Group, Inc....279

#3...Protocol for strain gauge installation...281

#4...Calibration of transducers and reproducibility of bite and EMG measurements...283

#5...Consent Form signed by normal subjects...291

#6...Consent Form signed by participating TMD patients...293

#7...Craniomandibular Index Examination form...295

CHAPTER 1

INTRODUCTION

1.I...STATEMENT OF THE PROBLEMS

1.II...OBJECTIVES

Chapter 1, Section I

STATEMENT OF THE PROBLEMS

The human jaw motor system is equipped with more muscle elements than are required to break up the processed and refined food consumed in many diets. Even though some of the apparent redundancy could be attributed to fine control of mandibular movements, a large part of the problem is deemed to be solved by the brain: how to allocate tensions among various jaw muscles or possibly among muscular compartments of these muscles to successfully generate a chewing force of the desired and precise magnitude and direction.

The number of possible solutions is infinite (Osborn and Baragar, 1985; Koolstra *et al.*, 1988; van Eijden *et al.*, 1988*b*) as is possibly true with other biological motor systems powered by groups of synergistic muscles (Dul *et al.*, 1984*a*). The lack of a known optimal solution for a given task has raised questions related to the neural control of movements and biomechanics: how to control a movement and how to maintain stability (Rosenbaum, 1990). As long as the number of muscles acting across an articulation exceeds the degrees of freedom of the joint, the control of movement is a problem; and whenever a force is applied, stability is a problem.

Muscle synergy is difficult to study. Most dynamic movements involved in chewing, speaking and walking rely upon the coordination of many complex variables: force, muscle length, stiffness, velocity, viscosity and others (Stein, 1982). Even though fictive movements can be studied, it remains difficult to understand how all the variables are controlled. A similar problem exists for relating a static force to the muscle tensions required to produce it. The direction of the force produced by a single muscle can be assumed to align with its longitudinal axis (provided the tendons of the muscle have small attachment areas). The direction of the force generated by a group of synergistic muscles, however, cannot be estimated this way. This is at least true with jaw closing muscles which add two further complex features: all are multi-pennate and most have broad attachment areas in the skull.

It has for long been conceived that ***efficiency***, among others (such as protection), may be the principle which governs distribution of tensions among an apparently redundant group of synergistic muscles (Rosenbaum, 1990). This concept is reflected in the quotation (page) from Henneman (1980) which preludes this thesis. There are, however, numerous variables associated with a skeletal muscle which can be optimized, to conform with some efficiency principle, using linear programming introduced by G.B. Dantzig in the 1940's for studying economics (Campbell, 1977). The following are a few examples in which objective functions have been optimized with linear programming models:

muscle torque (Uno *et al.*, 1980);
muscle stress (Dul *et al.*, 1984*a* and 1984*b*);
the total (jaw) muscle force (Osborn and Baragar, 1985);
the activity of the most active (jaw) muscle (Koolstra *et al.*, 1988);
muscle stiffness (Hasan, 1986);
jerk (Hogan and Flash, 1987);
task performance of antagonistic muscles (Oguztoreli and Stein, 1990).

The above postulated objective functions formulate some of the many fundamental concepts in biomechanics, a somewhat theory-rich (as compared to data-rich) discipline. Work in jaw mechanics in this laboratory was initiated in the early 1980's. Osborn and Baragar (1984 to 1992), using computer jaw modelling based on linear programming, studied various components of the human jaw motor system: *e.g.*

1). predicting jaw movements by using soft and hard tissue constraints (Baragar and Osborn, 1984);

2). minimizing the sum of the muscle tensions used to produce a given bite force (Osborn and Baragar, 1985);

3). comparing the directions of bite forces at incisors and the lower first molar used to maximize a static bite force or to maximize work efficiency (Baragar and Osborn, 1987);

4). estimating the direction of TM joint reaction forces (Osborn and Baragar, 1992).

These studies formulated the premise for the present research project which stemmed particularly from the hypothesis proposed in Osborn and Baragar (1985): there may be a shared common pattern of jaw muscle activity if the same efficiency principle is learned by a population dealing with the same foods and, therefore, exposing its jaw muscles to a similar environment. The present study aimed, by experimental approach, to prove or disprove (which will lead to revision of) the Osborn and Baragar's (1985) model. The experimental design was to study the behavior of jaw muscles when they perform standard tasks. Static bite forces, which are one form of the mechanical output of contracting jaw muscles, can be used as a type of standard task.

The human mandible is unique in that it has somewhat widely separated left and right temporomandibular (jaw) joints which must function in unison; the bilaterally linked mandible normally retains a wide range of movement trajectories as compared to other bilaterally linked joints (such as the atlanto-occipital joint). These features may have caused further complexity for the central nervous system to control jaw muscles, and yet adds the advantage that the mandible (lower jaw) has a limited range of motion as compared to most joints in the limb. Therefore, a static bite force, generated between the upper and lower jaws, can be readily controlled and measured.

To ensure that a bite force is used as a standardized task, both its direction and magnitude must be known. The direction of a bite force in three dimensions had never been reportedly measured when this project started. The development of a bite force transducer capable of measuring the direction of a bite force in three dimensions was then required for the project.

The overall activity of some jaw muscles can be estimated by measuring, with surface electrodes, the compound action potentials they generate while contracting. The action potential of a single motor unit or a single muscle fiber can be recorded with (invasive) intramuscular electrodes. Gross electromyography (EMG), as required for the present study in which the activity in a large volume of muscle was to be measured, provide somewhat more information about overall relative muscle force than intramuscular EMG (Hylander and Johnson, 1989). In addition, multiple intramuscular needle electrodes would be unacceptable to patients whose voluntary cooperation was required.

Temporomandibular disorders (TMD) are often manifested by jaw muscle pain and tenderness which may be accompanied by muscle fiber injuries. It seems probable that an injured muscle, upon the occasion when it might have been used, would be 'guarded' from being recruited into action and its function might be compensated for by the activation of another (others) in its synergistic group. If a sample of normal subjects (those without TMD) could be shown to use their jaw muscles in much the same way, then the pattern of jaw muscle activity associated with TMD patients may be sufficiently aberrant to be detected.

The present study was considered to be a pilot project which, incorporating a novice three-dimensional bite force transducer, was designed to explore and compare the co-activation patterns of some synergistic jaw closing muscles under normal and pathological (TMD) conditions. The development of a bite force transducer capable of measuring the direction of a bite force in three dimensions along with its magnitude, an important part of the present study, made it possible to standardize the mechanical output (force) of the jaw motor system and has the potential to study some of its sensory and motor components.

Chapter 1, Section II

OBJECTIVES

The objectives of the present study were as follows.

(1) To develop a force transducer capable of measuring simultaneously the magnitude of a bite force and its direction in three dimensions and, in association with the force transducer, to develop a feedback system which would allow a subject to 'see' the direction and magnitude of the bite force being produced.

(2) To study the relationship between the surface EMG activities of some jaw muscles and the mechanical force they produce in certain directions.

(3) To test whether equivalent bite forces of different directions on the left and right sides of the jaw yield mirror image activities of left and right jaw muscles.

(4) To discover whether normal subjects use similar patterns of jaw muscle activity when producing the same specified bite force.

(5) If the answer to (4) was positive, to test whether TMD patients with jaw muscle tenderness or injury would use different patterns of muscle activity.

CHAPTER 2

REVIEW OF THE LITERATURE

2.I...BITE FORCE AND BITE FORCE TRANSDUCER

- 2.I.1...Bite force
  - .a...Maximum voluntary bite force
    - .(1)...Magnitude
    - .(2)...Correlations
  - .b...Direction of the bite force

- 2.I.2...Bite force transducer
  - .a...Uni-directional transducers
  - .b...Multi-directional transducers

2.II...MUSCLES OF MASTICATION

- 2.II.1...EMG of jaw muscles during dynamic tasks
  - .a...Chewing cycle
  - .b...Mastication
  - .c...Jaw movement

- 2.II.2...EMG of jaw muscles during static tasks
  - .a...Isometric tasks: unknown direction of bite force
    - .(1)...Intercuspal clenching
    - .(2)...Changing muscle length
    - .(3)...Distribution of tensions among jaw muscles
    - .(4)...Linearity
  - .b...EMG correlated with the direction of bite force
    - .(1)...MacDonald and Hannam (1984*a* and 1984*b*)
    - .(2)...van Eijden and coworkers (1988*a* - 1991)

2.III...ABNORMAL JAW MUSCLES: BITE FORCE AND EMG

2.III.1...The silent period
2.III.2...Resting jaw muscles and hyperactivity
2.III.3...Maximum effort and length-tension relation
2.III.4...Muscle activity patterns during jaw movement
2.III.5...Effects of occlusal splint on muscle activity
    .a...Maximum inter-cuspal clenching
    .b...Postural and nocturnal muscle activity
2.III.6...Mandibular dyskinesia

Chapter 2, Section I

BITE FORCE AND BITE FORCE TRANSDUCER

2.I.1...BITE FORCE

Interest in human bite forces can be traced back to the 16th century (Carlsson, 1974; Helkimo *et al.*, 1977; Jenkins, 1978; Rowlett, 1932). Borelli, an Italian anatomist, in the year of 1681 used weights attached to a mandibular molar tooth and identified the maximum weight lifted by the mandible (Carlsson, 1974; Jenkins, 1978).

Since then, two types of bite force have been investigated with increasingly advanced apparatuses:

1) *Dynamic bite force* is generated during the chewing (*open-close-power stroke*) cycle associated with or without food intake. This may also be called chewing or masticatory force. In this case, the length of jaw closing muscles varies as the mandible is elevated and, therefore, the contraction is either isotonic or auxotonic. The maximum forces used during mastication are usually 1/10 to 1/3 of the maximum static (isometric) bite forces and obviously depend upon the hardness and texture of the food (De Boever *et al.*, 1978; Jenkins, 1978). Compared to numerous studies on static bite forces, there have been relatively few studies on chewing forces (Anderson, 1953, 1956*a*, 1956*b*; De Boever *et al.*, 1978; Graf *et al.*, 1974; Laurell and Lundgren, 1984; Lundgren and Laurell, 1984; Laurell, 1985; Neill *et al.*, 1989).

2) *Static bite force* is produced during isometric contraction of the jaw muscles. This is often called isometric bite force or simply the bite force. Static bite force is the focus of the studies in this thesis.

The SI unit of force is a *Newton* (*N*), a unit derived from $F = m \cdot a$ (*mass×acceleration*) according to Newton's second law. One Newton is 1 $kg \cdot m/sec^2$ and is the force required to accelerate a mass of 1 *kg* at the rate of 1 meter per second squared (Tilley, 1979).

2.I.1.a...Maximum voluntary bite force

The magnitude of a steady, isometric maximum bite force has been repeatedly measured in human subjects between different pairs or groups of upper and lower occluding teeth. It has also been correlated with various factors some of which are described below.

2.I.1.a.(1)...Magnitude

The maximum voluntary bite force (MVBF) is frequently measured unilaterally (on one side of the jaw) rather than bilaterally. The relatively few measurements on the bilateral maximum bite forces include those by Bakke *et al.* (1989), Devlin and Wastell (1985), Gibbs *et al.* (1986), Pruim *et al.* (1978), Pruim (1979), van Eijden *et al.* (1990), van Steenberghe *et al.* (1978*a*), *etc*. The average of the maximum bite forces measured when biting on both sides of the jaw is probably less than that measured on one side of the jaw (Bakke *et al.*, 1989). No significant difference has been found between the magnitude of bite forces measured on the right and left sides of the jaw (Bakke *et al.*, 1989 and 1990; Molin, 1972). Unless otherwise specified, the magnitude of the bite force described below refers to unilateral forces. In most cases, studies on natural teeth (rather than dentures) are cited.

1) ***In the incisor region***: Due to differences in tooth support and the length of the moment arms of jaw closing muscles, the maximum bite force generated in the incisor region is less than that produced in the molar region (Carlsson, 1974; Hagberg, 1987*a*). The ratio of maximal incisal bite force to maximal molar bite force is about 1:3 or 1:4. Incisal MVBF measurements are summarized in Table 1 (*p*.163).

2) ***In the premolar and molar regions***: The first molar (M1) is capable of producing the greatest bite force among all the teeth (Carlsson, 1974). Contrary to the general view, Mansour and Reynik (1975*a* and 1975*b*) found, in one subject, that MVBF between the second molars (M2) was 10% greater than that between M1s. The MVBF produced on premolars is lower than but comparable with that produced on the first and second molars. Maximum bite forces measured on premolars and molars are summarized in Tables 2 and 3 (*pp*. 164,165) respectively.

MVBF is frequently underestimated due to (1) the reluctance of subjects to exert the maximum effort (fear of pain and injury) and (2) lack of visual feedback of the force (Dahlstrom *et al.*, 1988). Apart from its role in evaluating TMD and other research considerations, the maximum bite force is of little interest from a clinical perspective since it is hardly ever used in mastication. Instead, submaximal bite forces at different levels, including those involved in daily chewing, are far more important in oral rehabilitation and prosthetic reconstructions.

2.I.1.a.(2)...Correlations

The magnitude of a maximum isometric bite force has been used to study, or been correlated with, the following factors.

1) ***Age, gender, and body build***:

During childhood, MVBF increases with age (Helle *et al.*, 1983). Adults have higher MVBF values than children (Bakke *et al.*, 1990; Proffit and Fields, 1983): more so in the molar region than in the incisor region (Helle *et al.*, 1983). As one ages the bite force decreases, especially for women (Bakke *et al.*, 1990; Helkimo *et al.*, 1977).

Males have a higher maximum bite force than females: again, more so in the molar regions (Bakke *et al.*, 1990; Helkimo *et al.*, 1977; Jenkins, 1978). The discrepancy between genders is, however, smaller than that for limb muscles (Linderholm and Wennstrom, 1970; Linderholm *et al.*, 1971). The explanation might be as simple as that jaws of both genders break the same food while males have a greater chance to exercise their limb muscles. This seems to be supported by the observation that the discrepancy in MVBF between males and females is less in complete denture wearers than in dentate subjects (Helkimo *et al.*, 1977).

In addition, there seems to be no correlation between bite force and the general body (limb) muscle strength (Helkimo and Ingervall, 1978). Athletes do not show greater MVBFs than non-athletes even though athletes tend to have generally stronger limb muscles (Jenkins, 1978). In the general public, it is possible that the bite force one can generate is comparable with or even greater than the load he or she can lift.

2) ***Population***:

Primitive people who chew thoroughly, eat tough food, and use their teeth as tools or even weapons have stronger maximum bite forces than those in more developed societies (Carlsson, 1974). Inuits (Eskimos) are among the few groups who may still eat tough foods as a regular diet; their maximum bite forces (*e.g.* 150 *kg*) are much higher than those (usually 40 - 70 *kg*, see above in 2.I.1.a) of the western populations (Jenkins, 1978; Waugh, 1937). Racial inheritance of powerful jaws may be another reason that Inuits can produce high bite forces (Jenkins, 1978). Thus, it seems true that the more developed a society is, the lower the average MVBF. However, the gap in bite forces between the Inuits and the more civilized societies is not rigidly bounded: Gibbs *et al.* (1986) reported that a (Caucasian) bruxer with hypertrophied masseters was able to produce 225 *kg* as the maximum bite force.

3) ***Craniofacial morphology***:

Both adults and children with long faces have lower MVBFs than those with normal-length faces (Proffit and Fields, 1983; Proffit *et al.*, 1983). A small gonial angle has also been shown to be an indicator of strong bite force capabilities (Ingervall and Helkimo, 1978; Rinqvist, 1973*a*). People with excess overbite seem to produce same amount of MVBF as subjects with normal overbite, while people with excess overjet may produce less bite force (Bakke *et al.*, 1990; Rinqvist, 1973*a)*. Sasaki *et al.* (1989) suggested that the volume of jaw muscles alone might account for the variation in bite forces among subjects whose craniofacial morphology may differ significantly.

4) ***The centric and eccentric application of the force***:

Intercuspation results in occlusion between lingual cusps of upper premolars and molars and buccal cusps of lower ones in normal condition. When the buccal cusps of upper premolars occluded with the buccal cusps of the lower premolars, the MVBF produced was lower than that in the normal position (Widmalm and Ericsson, 1982). MVBFs measured with the mandible in extreme lateral positions, in protrusion, and in retrusion were also lower than those when the measurement was made in the intercuspal position (Leff, 1966).

5) ***Increasing use of jaw muscles***:

The maximum bite force can be increased by exercise (*e.g.* chewing paraffin wax for a period of time) (Brekhus *et al.*, 1941; Ingervall and Bitsanis, 1987; Worner and Anderson, 1944; Yurkstas, 1953). All these studies indicate that human jaw muscles could potentially generate more force when they have been increasingly used for a prolonged period of time. Two factors during training may contribute to the increase in the maximum bite force: more strength in jaw muscles and increasing tolerance of periodontal tissues to pain (Jenkins, 1978; Ingervall and Bitsanis, 1987). The first factor has its physiological basis: (1) muscle fibers can generate more force by increasing their diameter as a result of training and (2) fiber types (type I and type II) may switch in favor of potentials to generate more force (Edstrom and Grimby, 1986; Salmons and Henriksson, 1981). The second factor refers to the possible increase in the firing threshold of periodontal nociceptors and remains controversial (Lund and Lamarre, 1973; Lavigne *et al.*, 1987).

6) ***Bruxism, tooth wear and attrition***:

Bruxism, grinding and clenching result in subconsciously increasing the use of jaw muscles. The MVBFs generated by subjects with these parafunctions have given contradictory results compared with control groups. Subjects with tooth grinding or clenching habits had greater incisal MVBFs. This was not true, however, with molars (Helkimo and Ingervall, 1978). No differences were found by Dahl *et al.* (1985) on anterior teeth and Lindqvist and Ringqvist (1973) on the molar teeth. Lyon and Baxendale (1990) found only slight differences in the endurance time when both groups sustained 50% MVBF during fatigue tests of jaw muscles. In conclusion, the majority of studies do not seem to support the concept that subjects with grinding or bruxing habits have higher MVBFs.

7) ***Prosthetic rehabilitation***:

Isometric MVBFs in full or partial denture wearers are much lower than those in dentate subjects (less than 1/3 as reviewed by Jenkins, 1978); the greater the number of natural teeth, the greater the MVBF (Helkimo *et al.*, 1977). Patients with implant dentures seemed capable of producing greater bite force than those with complete dentures (Hernandez and Bodine, 1969). However, denture wearers seem to be able to generate approximately the same amount of force during mastication (chewing) as dentate subjects (Yurkstas and Curby, 1953).

8) ***Separation between upper and lower jaws***:

After all the upper and lower teeth are lost, registration of the resting distance (freeway space) between upper and lower jaws is a vital step in successfully constructing complete dentures. For this reason, the length-tension relation of jaw closing muscles, which is the length at which MVBF is produced, has been of interest to prosthodontists and physiologists.

Two fundamental problems are still unresolved: (1) at what jaw separation can the greatest bite force be generated? (2) at what length can a jaw muscle exert the greatest tension? The first question cannot be thoroughly understood without fully addressing the second (see 2.II.2.a). The length at which MVBFs are obtained is summarized below. All the measurements on MVBFs for length-tension studies have been made with uni-directional force transducers.

Boos (1940) postulated that the maximum bite force in dentate subjects was produced with the natural teeth near occlusal contact (close to the mandibular rest position) based on his results on edentulous patients. Fields *et al.* (1986) did not observe a significant increase in MVBF between 2.5 *mm* and 6 *mm* jaw separation (between first molars) in both children and adults. Turker and Miles (1985) indicated that a decrease of bite force is greatest at intermediate gape (at 6 *mm* between incisors) and slight in the extreme jaw open and closed positions.

9) ***Local anesthesia***:

After the periodontal tissues of one pair of upper and lower teeth are anesthetized, would the MVBF be greater, lower than or the same as that of the predetermined? Answers to this straightforward question are conflicting.

Adler (1947) observed that surface anesthesia of the gingival tissue increased the threshold for detecting lateral and axial forces applied to a tooth. Blocking the inferior dental nerve increases the threshold for detecting axial forces up to 70%, and roughly doubled that for detecting lateral forces.

O'Rourke (1949) reported that MVBF increased by about 20% after maxillary OR mandibular block anesthesia was applied. O'Rourke also quoted Schroeder's (1927) results being that local anesthetics led to 70% increase in biting strength.

Lund and Lamarre (1973) observed a 40% decrease in the MVBF after applying infiltration anesthetics to periodontal tissues of upper and lower premolars; moreover, the MVBF gradually recovered as the effects of the local anesthetic were wearing off.

Van Steenberghe and De Vries (1978*b*) found an increased MVBF after infiltration anesthesia to unilateral upper and lower canines. Orchardson and MacFarlane (1980) also reported increase in the maximum bite force of canine and premolar areas after infiltration anesthesia was applied to these teeth.

Recently, Teenier *et al.* (1991) showed that there was no difference in both the MVBF between the occluding first molars and the EMG activities of some jaw closing muscles between the anesthetized and un-anesthetized side of the jaw. Mandibular anesthesia was administered by blocking the inferior dental and long buccal nerves and infiltrating the periodontal tissues around the lower first molar. Maxillary anesthesia was induced by buccal and lingual infiltration.

Some of these studies are summarized in Table 4 (*p.* 166).

2.I.1.b...Direction of the bite force

The direction of a bite force has been less frequently studied than its magnitude. Early theoretical calculations of bite force direction were done by Carlsöö (1952), and Schumacher (1961 according to Marklund and Molin, 1972). Experimental measurements of the bite force direction have been infeasible or inaccurate until the past few years.

Marklund and Molin (1972), and Molin (1972) measured components of maximum and submaximum bite forces in unknown directions with a uni-directional force transducer. In separate experiments they measured vertical, lateral, medial, protrusive and retrusive jaw closing forces. They found that (1) the maximum bite force used for protrusion considerably exceeded that for retrusion and for laterotrusion; and (2) the vertical MVBFs on the left and right sides of the jaw were not significantly different.

Since the 1970's, the application of engineering technology has permitted the directions of bite forces to be measured. Studies that investigated the direction of bite force include those by Hylander (1978) and van Eijden and coworkers (1988-91).

Hylander (1978) investigated the directions of the incisal bite force in the sagittal plane with two transducers of different thickness (10 and 30 *mm*). Submaximal (below 100 *N*) incisal bite forces were vertically or anteriorly directed, and assumed symmetrical, in all the subjects.

In a pilot study of two subjects, van Eijden *et al.* (1988*a*) investigated bite forces of 200 *N* in the vertical (perpendicular to the upper occlusal plane), 30° forward, backward, medial and lateral directions. The point of application was between the upper and lower first molars on the right side. Jaw separation (measured as interincisal distance) was 20 *mm* when the force transducer was placed at the canine-premolar region, and 28 *mm* at the second molar region. Maximum voluntary bite forces were estimated in various directions.

Van Eijden (1990) studied 250 *N* bite forces in vertical and 20° forward, backward, medial and lateral directions. The point of application was between the right first molars and bilateral premolars. The jaw separation was reduced to 16.0 ± 2.3 *mm* (mean ± S.D. in 7 subjects) irrespective of the point of application (with the same transducer).

Blanksma and van Eijden (1990) used a constant magnitude of 150 *N* in vertical, 20° anterior, anterolateral, lateral, postero-lateral, posterior, postero-medial,

medial and antero-medial (horizontally in 45° increments). The point of application was between the right second premolars.

Van Eijden *et al.* (1990) studied the same directions of bite force as in van Eijden (1990), while the bite force in this study was incremental (50 *N* up to 350 *N* in 100 *N* increments). Maximum voluntary bite forces in different directions were also measured.

2.I.2...BITE FORCE TRANSDUCER

When jaw closing muscles exert steady isometric contractions, the skull and mandible are stationary with the upper and lower teeth contacting either each other or a rigid object. During this state of equilibrium, a force transducer can be used to measure the static bite force (between upper and lower jaws) exerted by the muscles of mastication. There had been at least 50 bite force measuring apparatuses, often called gnatho-dynamometers, reported before the 1950's (Lofberg, 1960 according to Carlsson, 1974).

In the 1950's, the technical development of bonded foil strain gauges and piezoelectric materials (*e.g.* quartz crystal) facilitated increasingly accurate measurements of bite force. More bite force transducers, most of which were designed by dental researchers, have appeared since then. Measurements with these force transducers were often confined to maximum bite forces.

Following three decades of measuring the magnitude of bite forces with strain gauge and piezoelectric bite force transducers, knowing the directions of the forces became increasingly demanding (Graf *et al.*, 1974; Hylander, 1978; Marklund and Molin, 1972; Molin, 1972). This trend reflected the need for accuracy in describing force as a physical quantity. A force, as a vector, has the properties of magnitude, direction, and point of application. It is also described by its duration and frequency. The direction of a bite force is commonly referred to as that exerted on the maxilla relative to the mandible. The point of application, or the bite position, is the location between pairs or groups of occluding teeth.

A force transducer is composed of structural material (housing) and a sensor(s). Although more accurate measurements of the directions of bite forces are needed, the sensor materials in use at present are essentially the same as those which have been available since the 1950's - foil strain gauges and piezoelectric materials. Improvement in accuracy must therefore rely upon advancement in the design of the structural material on or in which the sensor is attached (*e.g.* measuring the direction of a bite force) of bite force measurements.

Since the direction of bite force is of primary concern in this study, the uni-directional *vs.* multi-directional bite force transducers are discussed below.

2.I.2.a...Uni-directional force transducers

A uni-directional bite force transducer is defined in this text as a device which measures bite force in only one direction, usually the vertical (perpendicular to the occlusal plane) or axial (along the longitudinal axis of a tooth).

Floystrand *et al.* (1982) designed a uni-directional transducer which has been extensively used by others (Bakke *et al.*, 1989, 1990; Dahl *et al.*, 1982; Hagberg and Hagberg, 1989). The bite force transducer incorporated two strain gauges on the top and bottom surfaces of a silicon beam. The two strain gauges formed two arms of a Wheatstone bridge and therefore the transducer had a half (Wheatstone) bridge configuration. The strain gauges with the metal frame were about 4 *mm* thick.

Another typical cantilever beam design was from Helkimo *et al.* (1975) whose force transducer was later used by Haraldson *et al.* (1985), Widmalm and Ericsson (1982), *etc*. One fork, withstanding 25 *kg* of force served for measuring incisal bite force and another, withstanding 100 *kg* for measuring molar bite force. The biting surfaces of the intraoral part of the transducer were covered with plastic.

The cantilever beam (like a clothes peg) has been a popular design of many bite force transducers including those used by Dechow and Carlson (1983), Duxbury *et al.* (1973), Helle *et al.* (1983), MacKenna and Turker (1983), Neill *et al.* (1989), Lewis and Yemm (1983), Rugh and Solberg (1972), Teenier *et al.* (1991), van Steenberghe and de Vries (1978*a*, 1978*b*) and Yemm (1977*a*).

Linderholm and Wennstrom (1970) developed a strain gauge force transducer which was later used by Ringqvist (1973*a*). The bulky components of the pistol-shaped bite force transducer were outside the mouth. Strain gauges were installed on two horizontal steel bars ($15\times15\times2\ mm^3$). The transducer yielded 4 *mm* jaw separation (measured as the distance between upper and lower central incisors) when placed between upper and lower premolars and molars. Other workers who have used the similar type of 'extra-oral' transducers are Coffey *et al.* (1989), Manns *et al.* (1979, 1989), Marklund and Molin (1972) and Molin (1972), Stegenga *et al.* (1990) and Williams *et al.* (1984*a*, 1984*b*, 1985).

Proffit *et al.* (1983), along with Fields *et al.* (1986) and Proffit and Fields (1983), reported the force-measuring capability of poly-vinylidene fluoride foil (PVF). PVF is piezoelectric and produces a current when compressed. A 30 *μm* thick strip of PVF was sandwiched between 2 *mm* thick stainless steel castings. When the transducer was placed between upper and lower teeth, it was compressed and well adapted to the contour of the cusps and fossae of the teeth.

The above uni-directional bite force transducers have the following disadvantages:

(1) The layout of the structural material (housing) of a bite force transducer has usually been a cantilever beam. It does not seem feasible to detect the direction of a bite force with this design.

(2) Unless bite pads (such as acrylic overlays) are used on the clenching (flat) surfaces of the transducer, the directions of different trials (even by the same subject) and the position of the bite are not reproducible;

(3) Due to great temperature variation compared to metal strain gauges, semiconductor gauges (as used in Floystrand *et al.*, 1982) are susceptible to inaccuracies although they may be more sensitive (higher gauge factors) (Cobbold, 1974). Metal foil strain gauges have largely replaced semiconductors as sensors used for bite force transducers.

2.I.2.b...Multi-directional force transducers

In recent years, force transducers capable of detecting both the magnitude and directions (in two or three dimensions) of a bite force have been reported. These include (1) a three component load cell designed by Watanabe and Hannam (1986), (2) a strain gauge rosette incisal force transducer developed by Hylander (1978) and (3) the three dimensional piezoelectric force transducer introduced by van Eijden *et al.* (1988*a*).

In an abstract Watanabe and Hannam (1986) reported a bite force transducer which incorporated three load cells oriented in different directions in a cast metal framework. The transducer was apparently used to record the magnitude and directions of bite forces. Further report of this transducer has not been found.

Hylander (1978) installed strain gauge rosettes on two lateral surfaces of plastic blocks of various size. Each strain gauge in a 3-element rectangular rosettes

(0°, 45°, 90° configuration; WA-06-060-WR-120, Micro-Measurements, Romulus, USA) formed its own Wheatstone bridge. Two grooves were cut into the top and bottom surfaces of plastic block to ensure reproducible bite position. The incisal bite force was assumed to be symmetrical and was not measured in the frontal plane.

A three-component piezoelectric force sensor is commercially manufactured by Kistler Corp. for industrial use. Van Eijden *et al.* (1988*a*) added two stainless steel plates to the 3-component sensor and later used it to measure the bite force in three dimensions. The magnitude and direction of a bite force was provided as a feedback to subjects on a computer screen.

A piezoelectric material such as a quartz crystal has the property of inducing voltage difference between two poles when it is mechanically deformed. The output voltage is proportional to the forces, which cause deformation, divided by the capacitance of the material (Webster, 1978).

The technical details of this commercial sensor are described as follows. Three quartz crystal disk pairs are welded in the stainless steel housing. One pair is sensitive to the vertical force along its axis, while the two others to horizontal forces in anteroposterior and mediolateral directions. Therefore, a force acting on the transducer is measured by the three pieces of piezoelectric material (Kistler Instrument Co., Technical Data). Piezoelectric bite force transducers (not necessarily with 3 dimensional capabilities) have also been used by others such as Fields *et al.* (1986), Graf *et al.* (1974), and Lindauer *et al.* (1991).

The thickness of the force transducer used by van Eijden and coworkers is 12 *mm* (10 *mm* sensor + the two 1 *mm* plates). The size of the sensor is 24×24×12 mm^3 (*length*×*width*×*height*). Two metal plates (along with acrylic) cover the whole upper and lower dentition and the sensor is targeted between pairs of occluding teeth. This may result in two potentially important problems: (1) a considerable amount of jaw separation cannot be avoided: when the transducer was placed between the upper and lower molars, 28 *mm* was the distance between central incisors (van Eijden *et al.*, 1988*a*); and (2) all the teeth in upper and lower dentition, other than the occluding pair under study, might also contribute to the recorded bite force. It has been shown that MVBF produced between several upper and lower premolars and molars was greater than between one pair of these occluding teeth (van Steenberghe and de Vries, 1978*b*).

The following conclusions can be drawn from the above directional bite force transducers.

(1) Composite (three dimensional) bite force measurement is difficult but feasible.

(2) If greater accuracy and reproducibility of a bite force measurement are required, the direction of the bite force must be known.

(3) Piezoelectric materials and strain gauges appear to be good force sensors. In the near future, transducers utilizing these materials are expected to predominate in the area of bite force measurement.

(4) The output from a strain gauge can become non-linear with the graded forces applied to it and is subject to temperature variations when it is installed on non-metal material (Perry and Lissner, 1962). This source of error did not seem to have been eliminated in some of the above studies.

(5) The thickness of the Kistler transducer modified by van Eijden and coworkers is one of its disadvantages. "The transducer requires a large mouth opening..." and "... measurement could not be performed at a smaller degree of mouth opening" (van Eijden *et al.*, 1988*a*). Van Eijden and coworkers also expressed interest in comparing "the results with those obtained by transducers operating at a smaller mouth opening".

(6) A *thin* three dimensional bite force transducer is required. It could readily be used to register bite force in a large variety of milieu; for example in studying the length-tension relationship of jaw muscles.

Chapter 2, Section II

ELECTROMYOGRAPHY OF NORMAL JAW MUSCLES

Electromyography (EMG) has been a major tool used to study the contraction of jaw muscles. Surface electrodes have been commonly employed to measure the gross activity of superficial masseter and anterior temporal muscles, while intramuscular (needle or fine wire) electrodes have been applied to study the above two muscles along with those, such as posterior temporalis, medial and lateral pterygoid muscles, digastric and other suprahyoid muscles which are difficult to access by surface electrodes. These non-invasive and invasive techniques have been used to assess the compound, motor unit and single-fiber action potentials of jaw muscles during dynamic and static tasks. This section will concentrate on, but not be limited to, studies measuring the compound muscle impulses using surface EMG recording techniques in human subjects.

2.II.1...EMG OF JAW MUSCLES DURING DYNAMIC TASKS

Dynamic tasks of jaw muscles include efforts of jaw muscles during a chewing cycle, mastication, jaw movement, *etc*. The integrated EMG activity of a skeletal muscle does not possess a linear relationship with the force generated during an isotonic contraction unless the contraction is within controlled speed and range (Bigland and Lippold, 1954; Close, 1964). Ahlgren and Owall (1970) note a linear relationship between the activity of human masseter and temporal muscles and the masticatory force exerted during chewing a homogeneous bolus (gum).

2.II.1.a...Chewing cycle

During an *open-close-power stroke* cycle, different groups of jaw muscles show characteristic activation patterns. Jaw opening movement is associated with activity in the anterior belly of digastric and the lower head of lateral pterygoid (Grant, 1973; Griffin and Munro, 1969; McNamara, 1974; Widmalm *et al.*, 1987). All the closing muscles (masseter, temporalis, and medial pterygoid) become increasingly active during the closing phase and reach the highest tension during the power stroke (Ahlgren and Owall, 1970; Griffin and Munro, 1969; Moller, 1974). Vitti and Junior (1970) found that, during the closing phase, the masseter (including its deep portion) and medial pterygoid are very active; the anterior temporalis shows little activity (see also Vitti and Basmajian, 1977). Wood (1987) indicated that the lower head of lateral pterygoid has a reciprocal role with the medial pterygoid during chewing.

2.II.1.b...Mastication

Deliberate unilateral (molar) chewing is a common task used to study jaw muscles during mastication. In this case, jaw closing muscles have often been studied by comparing their activity in the working and balancing sides.

The working side masseter and temporalis have greater EMG activity than the balancing side (Christensen and Radue, 1985*a*, 1985*b*; Stohler, 1986). These results are in agreement with the pioneer work by Moller (1966) in that the working masseter is more active; however, they are in conflict with Moller (1974) in that the working and balancing posterior temporal and anterior temporal muscles are equally active. Moller later attributed the equality between working and balancing temporal muscles to anterior temporalis being responsible for moving the mandible rather than for exerting the chewing force. In dogs, the balancing temporalis is much less active than the working; the working and balancing masseters, however, are about equally active (Dessem, 1989). Medial pterygoid is found to behave like masseter in that the working side is more active than the balancing (Moller, 1966 and 1974). The overall activity of jaw closing muscles during chewing gum might reach or exceed 50% of their maximum isometric activity (Moller, 1974); this, however, obviously depends upon either the force voluntarily used during chewing or the hardness of the material being chewed (Hagberg, 1986*a*). Jaw opening muscles, the digastric, mylohyoid and geniohyoid, show reciprocal activity to that of their antagonists, the jaw closing muscles (Vitti and Basmajian, 1977).

Less muscle activity is required during deliberate unilateral chewing than during natural (usually bilateral) chewing of apple and bread (Moller, 1966). Anterior temporalis appears to be the most active muscle among others during natural chewing. For example, anterior temporalis is found to be more active than either masseter or posterior temporalis; the latter, however, is constantly active (Moller, 1966). Sheikholeslam *et al.* (1980) also suggested that anterior temporalis is more active than masseter during deliberate chewing.

Incision is the first stage of chewing most foods. It was once believed that the temporalis seldom participated in incisal biting (*e.g.* Moller, 1966). Hylander and

Johnson (1985) suggested, based on their human and macaque data, that anterior and posterior temporalis, along with masseter, are all very active during incision. Vitti and Basmajian (1977) also found that incisal gum chewing involves activity mainly in the temporalis.

2.II.1.c...Jaw movement

A vertical jaw closing movement is predominantly associated with activity in temporalis (Carlsoo, 1952) along with other jaw closing muscles; the upper head of lateral pterygoid is also involved (Grant, 1973). Protruding the mandible without tooth contact does not involve any part of the temporalis (Vitti, 1971); the upper head of lateral pterygoid is very active (Carlsoo, 1956). Protrusion with tooth contact, on the other hand, involves anterior and middle temporal muscles (Vitti, 1971). Retrusion is associated with posterior temporalis (Ahlgren *et al.*, 1985; Vitti, 1971). Lateral chewing movements in humans are characterized by activation of the anterior and posterior temporal muscles (Vitti, 1971; Vitti and Basmajian, 1977). In pigs, lateral movement of the jaw is associated with working side masseter and balancing side posterior temporalis (Herring, 1976). Medial excursions involve deep masseter (Vitti and Junior, 1970). Vertical jaw opening movement is associated with jaw opening muscles which include digastric, mylohyoid and geniohyoid muscles; the lower head of lateral pterygoid was also active (Grant, 1973). Jaw opening muscles are also active during jaw closing against resistance (Carlsoo, 1952 and 1956).

2.II.2...EMG OF JAW MUSCLES DURING STATIC TASKS

Human mastication is as complex as other repetitive movement cycles such as locomotion and respiration. Jaw closing muscles are able to exert overwhelmingly greater power than their counterparts, jaw opening muscles. This may have raised the possibility that a considerable amount of bite force, generated by jaw closing muscles, is used to maintain equilibrium because jaw opening muscles contribute very little to the state of equilibrium. A simplified approach is to study how jaw muscles, as a synergistic group, are recruited during certain reproducible tasks. An immediately suitable task seems to be the bite force, the end result of the contraction of jaw muscles. As indicated in 2.I.1.b., bite forces can only be used as reproducible tasks if all variables of a bite force are known. The direction of a bite force is among these variables. In the following section, EMG studies of jaw muscles during performing isometric tasks of known and unknown directions of bite force are discussed.

2.II.2.a...Isometric tasks: unknown directions of bite force

Inter-cuspal clenching is a common task used to study the contraction of jaw muscles because it is readily reproducible. Inter-cuspation with natural teeth can be considered as the position at which jaw closing muscles have their minimal length. Tensions exerted by jaw muscles have been studied under graded incremental length starting from the inter-cuspal position. The relative contribution to a given bite force by different jaw closing muscles will also be discussed in this section.

2.II.2.a.(1)...Inter-cuspal clenching

When the direction of a bite force is not known, maximum inter-cuspal clenching becomes an alternative (and may well be effective) way for making seemingly equivalent measurements of muscle activities among different subjects. In addition, the inter-cuspal position is an integral part of every chewing stroke (Moller, 1974). Muscle activation patterns have been extensively reviewed by Wood (1987). The conclusions are taken from Wood's review wherever not specified.

Compared to the directional efforts from maximum intercuspation as discussed below, maximum *vertical* inter-cuspal clenching results in greatest activity in the superficial and deep masseters and anterior and posterior temporal muscles (Vitti and Basmajian, 1977; Wood, 1987). Medial pterygoid is generally also most active but not in all subjects (Wood, 1986*a*).

Subjects can exert maximum bite forces in different directions (within a limited range) during maximum inter-cuspation (all are compared with vertical maximum inter-cuspal clenching):

Anteriorly directed effort leads to (1) maximum activity in superficial masseter, medial pterygoid and the lower head of lateral pterygoid; (2) little activity in posterior temporalis; and (3) reduced activity in anterior temporalis and deep masseter.

Posteriorly directed effort results in (1) maximum activity in posterior temporalis and deep masseter; (2) little activity in superficial masseter, medial pterygoid and the lower head of lateral pterygoid; and (3) reduced activity in anterior temporalis.

Laterally or medially directed efforts give rise to (1) maximum activity in the lower head of balancing pterygoid and little activity in the working one; (2) strong activity in the working and little activity in the balancing temporalis (both the anterior and posterior); (3) intermediate activity in the working masseter and reduced activity in the balancing masseter (both the superficial and deep); and (4) low activity in working and high activity in balancing medial pterygoid.

The two heads of the lateral pterygoid muscle are peculiar: they contract independently and are essentially opposite in their actions (Grant, 1973; McNamara, 1974; Widmalm *et al.*, 1987). The upper head is less studied than the lower head whose action is still not clearly understood. Carlsoo (1956) showed that when an isometric load applied to the mandible was increased, the activity of the lower head was increased along with the temporalis.

2.II.2.a.(2)...Changing muscle length

The sarcomere length of the fibers in a skeletal muscle determines, among other things, the twitch tension a muscle fiber can generate, and hence, the resulting amplitude of its compound action potentials and its EMG activity.

As the length of an isolated frog muscle fiber is increased, changes in the twitch tension it exerts have been well understood (Gordon *et al.*, 1966). A plateau of constant maximum tetanic tension has been found at sarcomere lengths of about

2.0 to 2.4 *μm* (about 50 - 60% of the maximum length). The tension declines either above or below this range. This classic work, indicating the overall shape of the length-tension curve, by Gordon, Huxley and Julian has proved to hold for mammals (*e.g.* Rack and Westbury, 1969 in the cat soleus muscle). The length-tension relationship has been studied in animal jaw muscles. Either the muscle (Nordstrom and Yemm, 1974) or its innervating motor nerve (Mackenna and Turker, 1978) is stimulated supra-maximally to obtain maximum tetanic tension when the sarcomere length varies by changing the gap between the upper and lower jaws. In human jaw muscles, the length-tension relation has been investigated by directing subjects to voluntarily produce their maximum bite forces at various degrees of mouth opening.

1). ***Changing sarcomere length***

According to the classic length-tension curve a sarcomere, the morphological unit of a skeletal muscle fiber, can be lengthened to an extent at which the maximum tetanic tension is produced. This length has been found to be 2.2 - 2.5 *μm* (about 70% of the maximum length) in the rabbit superficial masseter (Weijs and van der Wielen-Drent, 1983) and is consistent with the findings in limb muscles described above. This seems to correspond to the resting length (2.0 - 2.23 *μm*) of sarcomeres in the rat deep masseter when the teeth are in occlusion (Nordstrom and Yemm, 1972).

Herring *et al.* (1984) and Herring (1991), in two review articles, indicated that the resting length of sarcomeres in different vertebrate muscles is roughly constant, while the number of sarcomeres, even in adult muscles, can change due to functional demands. In addition, the resting sarcomere length of different jaw muscles or different groups of fibers within a single muscle may not be strictly equal due to the following factors. (1) Different muscles: The resting length was found to be in descending order in the following three muscles of the American opossum: temporalis, masseter and medial pterygoid (Hiiemae and Thexton, 1971; Thexton and Hiiemae, 1975). (2) Different parts of a muscle: Nordstrom *et al.* (1974), by correlating sarcomere length to jaw separation in the rat, showed that as jaw separation increases anterior masseter is stretched more than posterior masseter and temporalis. Van Eijden and Raadsheer (1992) showed that the sarcomeres in the superficial masseter are 6% longer than those of the deep masseter within which the sarcomeres of the anterior fibers are 8% longer than the posterior fibers. (3) Fiber types: It is not known whether the resting length is related to various types of muscle fibers (*e.g.* type I, IIA and IIB) contained in a muscle.

A practical way to make the length-tension relations in animal jaw muscles comparable to the situation in humans (discussed below) is to measure the maximum tetanic tension at various separations between upper and lower jaws. Mackenna and Turker (1978) found that the maximum twitch tension in cat masseter is produced at about maximum jaw separation (25 to 30 *mm*). This is far from agreement with Nordstrom and Yemm's findings (1974) of 8 *mm* (50% of maximum opening) of jaw separation for the rat masseter. However, Nordstrom and Yemm (1974) also noted that in some cats the peak tension is produced at maximum opening.

2). Changing jaw separation (muscle length)

The length-tension curves observed in an animal muscle, however, may not necessarily be similar to that in an equivalent human muscle (Dowben, 1980; Nordstrom and Yemm, 1974). Furthermore, the clinical jaw rest position might not coincide with the length of isolated jaw muscles at which its greatest tension is exerted (Boucher *et al.*, 1959). The reason might simply be that the maximum bite force generated in humans reflects the maximum resultant tension of all the jaw closing muscles rather than that of any single muscle.

Submaximal bite forces have been used to study the length at which jaw muscles exert the greatest tension. With the canine-premolar bite force kept constant, peak EMG activities of unilateral masseter and temporalis are registered at both slight and maximum jaw separations (range: 7 - 40 *mm* at the canine-premolar region) (Manns *et al.*, 1979; Manns and Spreng, 1977); lowest EMG activity is obtained at intermediate jaw separation (15 - 20 *mm*). In contrast, if the EMG is maintained constant, the peak bite force is exerted at the same intermediate jaw separation (15 to 20 *mm*). Storey (1962) compared EMG activity at bilateral submaximal bite forces up to 3 *kg* with jaw separations from occlusion to 20 *mm* opening; EMG activity in unilateral masseter and temporalis muscles was measured. As the force is maintained, EMG activity drops at the mandibular rest position.

Garrett *et al.* (1964) found that minimal EMG activity is detected at 17 to 27 *mm* of opening with a constant bite force.

Mackenna and Turker (1983) showed a similar range at which the maximum incisal bite force is produced (14 to 20 *mm*; 1/2 to 1/3 of the maximum opening); however, the maximum masseter EMG activity is recorded at the minimum studied jaw separation (7.5 *mm*). Lindauer *et al.* (1991) found that EMG activity (absolute EMG voltages) is greater at 8 *mm* molar separation than at 10 *mm*.

It is generally accepted that skeletal muscles exert their maximum isometric tetanic tension at 100 - 120% of their resting length (Close, 1972). For a whole muscle, the length at which maximum tetanic tension can be produced is defined as the optimal length of that muscle (Close, 1972). It seems that studies determining the resting length of jaw muscles, which is very possibly different from the rest position of the mandible, are lacking with few exceptions. However, it seems certain that the mandibular rest position (corresponding to a jaw separation of 2 to 4 *mm*) is less than the vertical dimension at which EMG activity in jaw closing muscles is minimal (Lund and Widmer, 1989).

2.II.2.a.(3)...Distribution of tensions among jaw muscles

Do masseter and temporalis, two amongst closely co-activated jaw closing muscles, have different recruitment patterns? If so, would they contribute to a given bite force proportionally in some fixed ways? The few studies using bite force as tasks measured with uni-directional force transducers have all reported great variation among subjects.

At low levels of inter-cuspal clenching, up to 20% of the maximum masseter EMG, activity in the bilateral anterior temporal muscles tends to dominate. The bilateral superficial masseters, on the other hand, are increasingly recruited at between 20% to 50% of the maximum masseter EMG activity (Naeije *et al.*, 1989).

Hagberg *et al.* (1985) showed that the two muscles have different recruitment patterns by breaking the whole regression curve of EMG *vs.* bite force into two fragments (0 to 40% and 60 - 100 % MVBF between the occluding first molars). However, when the absolute EMG voltages are converted into percentage units, the two muscles seem to be both recruited to about 20% of their corresponding maximum voluntary contraction during producing 40% of MVBF.

Analysis of the data from Bakke *et al.* (1989) reveals that the left and right temporal muscles (both the anterior and posterior) and superficial masseters have roughly the same percentage of the maximum activity, at 25% and 50% of MVBF, except for the balancing posterior temporalis.

When submaximal unilateral bite forces (50 *N*, 100 *N* and 200 *N*) are produced, the working anterior temporalis has the greatest activity (absolute EMG microvolts) followed by the working posterior temporalis. The working masseter almost always has the lowest activity (Haraldson *et al.*, 1985).

Guelinckx *et al.* (1986) found that, after bilateral masseters are removed from the rabbit, the incisal bite force drops by 65% and anterior temporal muscles are more resistant to fatigue. These results indicate that masseter and anterior temporalis closely collaborate to produce a bite force.

2.II.2.(a).4...Linearity

As early as the 1950's, an approximately linear relationship was found between the integrated EMG activity of a skeletal muscle and the mechanical force it produces (Lippold, 1952; Inman *et al.*, 1952). The linearity is even preserved in fatigued muscles (Edward and Lippold, 1956; Stephens and Taylor, 1972) and muscles which suffer from dystrophy due to diseases (Leman, 1959*a* and 1959*b*). Contradictory results, however, have suggested that such a linear relationship might change especially at high force levels and EMG amplitude might increase as the square root of tension (Bernshtein, 1967; Fuglsang-Frederikson *et al.*, 1984; Libkind, 1972*a*, 1972*b*; Kuroda *et al.*, 1970; Moore, 1967; Zuniga and Simons, 1969). Milner-Brown and Stein (1975) studied the surface EMG contributed by individual motor units and concluded that the peak-to-peak tension exerted by a motor unit does increase as the square root of the threshold force at which the unit was recruited but the rectified surface EMG still maintains an approximate linear relationship with the force.

The classic linear relationship between force and EMG has frequently been shown to hold in jaw muscles (*e.g.* Desmedt and Goudaux, 1979; Goldberg and Defler, 1977; Yemm 1977*a*).

Yemm (1977*a*) noted a fairly linear relation between maintained isometric bite forces on unilateral premolars (up to 6 *kg*) and the surface EMG activity of masseter and temporalis for a duration of 1 minute. During the surface EMG recordings, he also found a linear relationship between the voluntary force at which units were recruited and their twitch tensions; these results suggest that human masseter and temporalis recruit their motor units in an orderly and similar fashion following Henneman's size principle. Yemm also pointed out, unusually, that all the jaw closing muscles contributed to the measured bite forces.

With surface EMG, Kawazoe *et al.* (1979) also found linearity between muscle tensions of human masseter and temporalis and the bite forces produced in both second premolars and molars. The correlation coefficients, ranging from 0.96 to 0.99, were calculated with the best parts of both the EMG and force curves over 15 minute periods of isometric clenching at about 20 *kg*. The regression lines for the masseter are steeper than those for temporalis.

Contrary to the classic observation of linearity between integrated EMG and mechanical force, some workers have reported non-linearity between bite force and EMG activity measured from one or more jaw muscles (Devlin and Wastwell, 1985;

Hagberg *et al.*, 1985; Haraldson *et al.*, 1985; Moller, 1966; Pruim *et al.*, 1978; Wastell and Devlin, 1987).

Devlin and Wastell (1985) showed that, during either fast or slow clenching on a bite force transducer for less than one second, integrated EMG of masseter drops as the bite force approached the maximum. Wastell and Devlin (1987) repeated the experiment and obtained similar results.

Hagberg *et al.* (1985) found that the human masseter shows a non-linear increase in its EMG activity if the bite force was above 60% of maximum while the temporalis shows a linear increase.

The possible non-linearity and the above discrepancy in recruitment patterns among jaw muscles have led to the concept that normal human subjects use their jaw muscles in different ways for producing a somewhat similar task. A careful look into the above discrepancies, however, revealed the following problems.

(1) When producing static and isometric tasks, jaw muscles (masseter and temporalis have usually been used as models for EMG studies) exert tensions which may vary as the direction of the bite force changes; a change in force direction may either lead to a more significant recruitment in one muscle or selectively contribution from a specific elements in a muscle. Obviously, this problem cannot be appreciated with a uni-directional bite force transducer.

(2) When the relation between force and integrated EMG is examined among a group of synergistic muscles, recruitment patterns of all the muscles should be

considered. The slow-down in the recruitment of one muscle may be compensated for by increased recruitment of a partner.

(3) The amplitude of EMG reflects recruitment patterns of various types of muscle fibers contained in a muscle; therefore, the position of electrodes may change the proportions of slow and fast fibers being recorded.

(4) Caution should be taken towards comparing absolute EMG voltages among subjects. Percentages of maximum voluntary contraction seem to overcome the problem of electrode position and inter-electrode distance, both of which affect the absolute surface EMG amplitude; but percentages of maximum voluntary contraction become meaningful only if proper maximum values are established (see 3.III.2).

2.II.2.b...EMG Correlated with directions of bite force

Without knowing the direction of a bite force produced during isometric contractions of jaw muscles, it is difficult to compare the behavior of jaw muscles among subjects. In addition, because of the large variety of bite force tasks which have been studied and differences in EMG techniques, most previous measurements of the EMG activity of jaw muscles during isometric contractions are not quantitatively comparable and comparisons have been considered inconclusive. Lack of accuracy and reproducibility of bite force tasks is probably the key factor, rather than differences in EMG recording techniques (absolute EMG amplitude being an exception), which accounts for many of the discrepancies between results.

In 1984, MacDonald and Hannam (1984*a* and 1984*b*) used plastic occlusal stops to direct subjects to bite into various directions. Since 1988, the availability of a commercial multi-directional force transducer has enabled van Eijden and coworkers to study jaw muscle activity under controlled directions of bite forces.

2.II.2.b.(1)...MacDonald and Hannam (1984a, 1984b)

The plastic occlusal pads used by MacDonald and Hannam (1984*a* and 1984*b*) prompted subjects to produce maximum voluntary bite forces in different directions. EMG recordings of all the jaw closing muscles show the following results: (1) vertical maximum inter-cuspal clenching gives rise to the greatest activity; (2) protrusive incisal clenching is associated with more activity in masseter and medial pterygoid; (3) temporalis is the predominant muscle activated to produce a retrusive bite force; little activity is found in other muscles; (4) lateral clenching is characterized by great activity in working temporalis and balancing medial pterygoid.

2.II.2.b.(2)...van Eijden and coworkers (1988 - 1991)

Van Eijden *et al.* (1988*a*) set the magnitude of the bite force at 200 N and studied effects of changing directions (30° from the vertical) on the raw EMG activity of superficial masseter, and anterior and posterior temporalis in two subjects. This work is essentially a technical report of their modification and application of the three dimensional bite force transducer manufactured by Kistler Co. Little attempt was made to analyze the EMG results.

Van Eijden (1990) fixed the magnitude of bite forces at 250 *N* and studied muscle activation patterns when the force was applied to unilateral canines, second premolars and second molars. Vertical, anterior, lateral, posterior, and medial bite forces were correlated with EMG activity of the masseter, and the anterior and posterior temporal muscles. (1) More muscle tension is required for a given bite force at the anterior part of dental arch than the posterior part. (2) Variation in muscle activity is small for anterior temporalis and large for posterior temporalis and masseter. (3) All muscles are always active even in directions in which they contract against their favorable lines of action. (4) The masseter is most active during anterior and vertical bites and much less active during posterior bites. (5) For a lateral bite working masseter shows little activity and the balancing masseter shows great activity. The reverse is true for a medial bite. (6) The working anterior temporalis is most active for a lateral bite and least active for a medial bite: the reverse is true for the balancing temporalis. (7) The working posterior temporalis has great activity for a medial bite and little activity for a lateral bite: the reverse is true for the balancing temporalis.

Blanksma and van Eijden (1990) used fine wire electrodes to measure activities in three portions (anterior, middle and posterior) of the temporalis. Variation due to changes in the directions of bite force is smallest for anterior temporalis and greatest for posterior temporalis. All three portions show greatest EMG activity when the bite force is in a postero-lateral direction.

Van Eijden *et al.* (1990) studied muscle recruitment patterns when incremental bite forces in different directions were exerted. Bite forces used are 50 to 350 *N* (in 50 *N* increments) and a maximum in each of the directions. The working-side muscles are most active during lateral biting and least active during medial biting: the reverse is true for the balancing-side muscles. Slight differences are found for muscle activities during vertical, anterior and posterior biting.

The following conclusions can be drawn from the above series of studies by van Eijden and coworkers. (1) All muscles (including all portions of the temporalis) are always active during any single task. (2) When the direction of a bite force changes, anterior temporalis shows little variation in its activity and the posterior temporalis and masseter show significant variation in their activities. (3) There may exist a specific pattern of muscle activity in normal subjects with respect to a specific direction of the bite force. (4) Fixed lines of action in jaw muscles do not seem to be sufficient to explain the patterns of jaw muscles as a synergistic group during producing a large variety of bite force tasks.

Chapter 2, Section III

ABNORMAL JAW MUSCLES: BITE FORCE AND EMG

Temporomandibular disorders (**TMD**) are characterized by two major manifestations: joint dysfunction and muscle trauma (Bell, 1989; Laskin, 1969; Clark *et al.*, 1989*b*). Joint dysfunction is manifested by limited or irregular mandibular movements, traumatic joint injury, arthralgia, osteoarthritis, bone degeneration, joint noises and disk displacement. Muscle trauma, on the other hand, is manifested by muscle pain and tenderness (myalgia), spasm, bruxism, myositis, protected muscle splinting, lack of coordination and dyskinesia (Ash, 1986; Clark *et al.*, 1989*b*; Hutchins and Skjonsby, 1990; Talley *et al.*, 1990). Recently TMD has been suggested to be a neurological disorder (Storey, 1992).

Abnormal muscle behavior of sufficient intensity and duration may cause some of the above joint problems (Clark *et al.*, 1989*b*; Dahlstrom, 1989; Laskin, 1969; Laskin and Block, 1986). Since TMD has been increasingly recognized during the past two decades, attempts have been made to find jaw muscle indicators of diagnostic value for this condition. There seems little doubt that some of the jaw muscle indicators (discussed below) measured in TMD patients deviate from those in normal subjects (those without TMD). But until it is understood how these indicators are linked to symptoms and signs associated with TMD, their value as diagnostic tools remains empirical and unreliable.

Occlusal splints (splints or inter-occlusal orthopedic appliances) are frequently prescribed for TMD patients. Their success and failure have rarely been analyzed in relation to biomechanics and neuromuscular control mechanisms (Boero, 1989;

Clark, 1984*a*; Holmgren *et al*., 1990). A rather detailed summary is provided about the effects of occlusal splint therapy on the EMG activity of jaw muscles as revealed by previous studies.

2.III.1...THE SILENT PERIOD

The silent period was one of the first indicators recognized as having a potential diagnostic value for TMD. Symmetrical silent periods in the bilateral jaw closing muscles can be detected by EMG following tooth contact lasting about 15 to 35 milliseconds (*ms*) (Bailey *et al*., 1977; Bessete *et al*., 1971; Griffin and Munro, 1969; Hannam *et al*., 1969 and 1970; Stohler and Ash, 1984). Following a briefly reduced period of activity, jaw closing muscles are re-activated for about 50 - 75 *ms* in a chewing cycle (Ahlgren, 1966; Moller, 1966; Stohler and Ash, 1984).

In TMD patients the silent period is lengthened up to 152 *ms* (Bailey *et al*., 1977; Bessete *et al*., 1971; Stohler and Ash, 1984; Widmalm, 1976; Zulqarnain *et al*., 1989). The duration may match the severity of TMD symptoms and signs and return to the normal range after occlusal splint therapy (Bessete *et al*., 1971). Thus, the silent period has been recommended as a diagnostic measure of the extent of TMD and an objective method for monitoring the effectiveness of TMD therapies (Bessete *et al*., 1971).

An association between the silent period and TMD is, however, not universally accepted (Hellsing and Klineberg, 1983). Hellsing (1988), after reviewing various ways of measuring the silent period, concluded that although the silent period in TMD patients was prolonged, its value as a diagnostic tool was still doubtful due to the variation between individuals, recording techniques and eliciting methods which lead to discrepancies of 5 to more than 100 *ms* (also van der Glas *et al.*, 1984). In addition, there is a large overlap in the duration of the silent period between TMD patients and normal subjects (Hellsing, 1988).

Whether or not mechanically stimulating a tooth inhibits the jaw elevator muscles and, hence, produces a silent period, is still unsettled (Stohler and Ash, 1984). Tapping on the chin or a tooth during maximum intercuspal clenching has been the most frequently used method to induce a silent period (Bessete *et al.*, 1971). Such mechanical stimulation may, through vibration, directly stimulate the muscle spindles of the jaw closing muscles. Electrical stimulation, therefore, may be a better choice (Hannam *et al.*, 1970; Yemm, 1972*a* and 1972*b*).

It is also unclear what peripheral receptor(s) initiate the reflex which leads to the transient inhibition of jaw closing motoneurons. Periodontal mechano-receptors (PMR), jaw muscle spindles and nociceptors in the oral mucosa have been implicated (Ahlgren, 1969; Griffin and Munro, 1969). Stimulating the inferior alveolar nerve of dogs at a strength which activated low-threshold PMRs inhibited the jaw closing muscles (Dessem *et al.*, 1988). Local anesthesia applied to the periodontal ligament of a central incisor abolished the silent period which had previously been elicited by tapping this tooth (Sessle *et al.*, 1972). In contrast, Matthews and Yemm (1970) found that the silent period induced in edentulous subjects wearing full dentures was similar to that in those with natural teeth. Matthews and Yemm's result seems to indicate that PMRs are at least not the only receptors for the pathway responsible for inducing a silent period. For the nociceptors in the oral mucous membrane, Yemm (1972*a* and 1972*b*) showed that electrically stimulating oral mucous membrane elicited silent periods in masseter and temporalis.

2.III.2...RESTING JAW MUSCLES AND HYPERACTIVITY

In the mandibular rest position the upper and lower teeth are separated by a wedge-shaped space of 2 to 8 *mm* which is often clinically referred to as the *freeway space*. To prevent further downward displacement of the mandible in an upright subject, an upward directed force must cancel the force of gravity.

One or more jaw closing muscles appeared to sustain some low level activity to maintain mandibular posture (Lund and Widmer, 1989; Moller, 1985). Temporalis has been found to be responsible for elevating the mandible against gravity (Ahlgren *et al.*, 1985; Burdette and Gale, 1990; Ingervall and Thilander, 1974; Jenkins, 1978; Vitti and Basmajian, 1977). Horizontally oriented fibers in the posterior temporalis may be assisted by some obliquely oriented fibers in the middle temporalis to hold the mandible up against the downward pull of the gravitational force. Anterior temporalis might also be used (Holmgren *et al.*, 1985), but deep masseter did not seem to be involved (Vitti and Junior, 1970).

Body posture apparently affects the muscle activity required to maintain mandibular posture. A supine position reduced the activity in temporalis (Holmgren *et al.*, 1985; Jenkins, 1978; Lund *et al.*, 1970; Moller *et al.* 1971).

The visco-elastic properties of muscles and their related connective tissues may help to maintain the rest position and might be the sole factor as deceased rats were shown to have a normal jaw resting position (Yemm and Nordstrom, 1974). This view seems to be supported by the observation that no motor units in posterior temporalis were active at the mandibular rest position (Eriksson *et al.*, 1984). However, a few motor units contracting at low frequency might have been overlooked (Moller, 1974).

Two questions have been asked regarding the possible link between postural EMG activity and muscle pain in TMD patients. (1) Is an injured jaw closing muscle hyperactive while maintaining the mandibular rest position? (2) Is the hyperactivity, if it exists, linked to fatigue or pain in the jaw muscles of TMD patients?

Many workers have found that the postural EMG activity of the masseter and temporal muscles in TMD patients is greater than that of normal subjects or that of the same patients prior to treatment (Burdette and Gale, 1988; Dahlstrom *et al.*, 1985*b*; Lous *et al.*, 1970; Moller et al., 1971; Sheikholeslam *et al.*, 1980 & 1982; Shumann *et al.*, 1988). The increased activity was probably more pronounced in anterior temporalis (Lous *et al.*, 1970; Sheikholeslam *et al.*, 1982). Dahlstrom (1989) concluded that hyperactivity due to spasm of temporalis coincided with some of the symptoms and signs associated with TMD.

In contrast, other studies failed to detect hyperactivity in the jaw muscles of TMD patients who were maintaining the mandibular rest position (Majewski and Gale, 1984; Sherman, 1985). Lund *et al.* (1989) stated that some of the studies which found increased postural EMG activity in TMD jaw muscles had failed to match a control group under equivalent conditions and to apply statistics. They concluded that there was no solid evidence to indicate an increased postural EMG activity in TMD patients as compared to that of normal subjects (also Lund and Widmer, 1989; Yemm, 1985).

While controversy surrounds whether there is muscle hyperactivity in TMD patients, it is usually assumed that prolonged hyperactivity would cause fatigue in jaw muscles which, in turn, could lead to pain.

Some workers have found that postural hyperactivity of jaw muscles seems to be correlated with myalgia (Clark *et al.*, 1979; Mercuri *et al.*, 1979; Sheikholeslam *et al.*, 1982). Injection of lidocaine into the painful (unilateral) masseter and anterior temporalis reduced their postural EMG activity (Hagberg, 1987*b*). In contrast, Majewski and Gale (1984) clearly showed that pain in the area of anterior temporalis on one side was not associated with postural hyperactivity in the ipsilateral anterior temporalis. Martin and Matthews (1978) also failed to correlate headache with excessive tension in some head and neck muscles.

Sustained jaw muscle contractions may well contribute to pain (Christensen, 1985; Clark and coworkers, 1984 - 89). However it is not known whether postural hyperactivity, which accounts for a small fraction of the maximum voluntary activity, leads to fatigue.

2.III.3...MAXIMUM EFFORT AND LENGTH-TENSION RELATION

There is overwhelming evidence that the maximum voluntary bite force (MVBF) observed in TMD patients is smaller than that in normal subjects (Helkimo and Ingervall, 1978; Helkimo *et al.*, 1975; Jenkins, 1978; Molin, 1972, *etc*). Markland and Molin (1972) found that TMD patients developed smaller forces than normal subjects when exerting the maximum protrusive, retrusive, and lateral (to the left and right sides) bite forces. There is also evidence that MVBF increased as symptoms improved during treatment (Helkimo *et al.*, 1975). In addition, the EMG amplitude recorded during maximum inter-cuspal clenching was much lower in TMD patients than in normal subjects (Dahlstrom and Haraldson, 1985; Sheikholeslam *et al.*, 1980).

In contrast, Hagberg *et al.* (1986*b*) and Gelb (1990) both found no difference in MVBF between normal and TMD groups. Helkimo *et al.* (1975) did not observe a significant difference in bite force between the affected and unaffected sides of the face. Markland and Molin (1972) found no difference in the maximum jaw closing force when TMD patients bit onto the healthy or affected side. Splint therapy did not seem to change the EMG amplitude during maximum inter-cuspal clenching (Sheikholeslam *et al.*, 1982).

There is little doubt that TMD patients are not willing to produce as much bite force as normal subjects despite having a normal muscle mass. The unwillingness to do so may well be due to pain in their jaw muscles or jaw joints. Because MVBF varies considerably among normal individuals, its usefulness as a diagnostic tool is doubtful.

The length-tension (force) relation in normal human subjects and experimental animals has been discussed in 2.I.1.a and 2.II.2.a. Two questions are still unsettled: (1) at what amount of jaw separation is the greatest bite force produced? and (2) what is the resting length of jaw muscles? One study has addressed the differences in the length-tension relation between TMD patients and normal subjects. Gelb (1990) found that normal subjects exerted maximum bite forces at jaw separations of 5 *mm* while for some TMD patients with muscle pain (and without joint problems) the separation was 8 to 9.5 *mm*. However, jaw separation was only measured from 3 to 12.5 *mm*. The EMG activity of jaw muscles was not measured.

2.III.4..MUSCLE ACTIVITY PATTERNS

Painful jaw muscles of TMD patients may be recruited differently from those of normal subjects. Until recently, such possible differences have not been studied.

Naeije and Hansson (1986) used 50% masseter EMG during maximum intercuspal clenching as a standard and found that myogenous TMD patients had higher average absolute EMG voltages in masseter and temporalis than arthrogenous patients. Hagberg and Hagberg (1989) indicated that recruitment of motor units in jaw muscles of TMD patients might be hindered, especially at high force levels.

Nielsen *et al.* (1990) observed the following differences in the activity pattern of the masseter and temporal muscles in normal and TMD subject during some rapid jaw movements and intercuspal clenching.

(1) With pain in some jaw and neck muscles, the anterior temporalis was less often used and its activity was low during (a) rapid vertical jaw closing, (b) retrusion from the intercuspal position, (c) latero-trusion to the side of painful muscle, and (d) chewing gum.

(2) With pain in some jaw and neck muscles, the masseter was less frequently used or its activity was smaller during (a) rapid vertical closing, (b) intercuspal protrusion, (c) incisal clenching, and (d) chewing gum.

(3) With pain in at least one masseter (without painful neck muscles), the anterior temporalis was less frequently used or its activity was smaller during the tasks specified in (1). In fact, the activity of anterior temporalis was always lower regardless of the source of pain (as identified clinically).

(4) The activity of masseters were NOT different between those subjects with temporomandibular joint(s) degeneration and normal subjects.

In TMD patients the jaw muscles may be protectively splinted during jaw opening movements (reviewed by Clark *et al.*, 1989*b*; Talley *et al.*, 1990). Injured jaw muscles are likely to be guarded in order to avoid pain or joint problems (such as clicking or lock). Intuitively this would result in abnormal muscle activity. However, without sufficient information about how normal jaw muscles are recruited, it is not possible to quantitatively address this problem in TMD patients.

2.III.5...EFFECTS OF OCCLUSAL SPLINTS ON MUSCLE ACTIVITY

Occlusal splints are commonly used by dental practitioners to treat some TMD conditions, especially those with myalgia (Ash and Ramfjord, 1982; Clark, 1984*b*). Basically, there are five types of splint: stabilization, repositioning, pivot, soft and the bite plane splints (Boero, 1989; Major, 1988). Unless otherwise specified the splints used in the studies quoted below are full-arch stabilization splints.

The overall effectiveness of splint therapy may be as high as 70 - 90% of treated patients (Clark, 1984*a*; Zarb and Speck, 1979). Greene and Laskin (1972) argued, however, the effectiveness of the splint therapy was often evaluated from short-term subjective responses from patients. To overcome this shortcoming, EMG activity of jaw muscles has been used to assess their effectiveness. It has been used for both normal and TMD subjects during maximum inter-cuspal clenching and while maintaining mandibular posture. Nocturnal muscle activity has also been studied as an indicator of pathology.

2.III.5.a...Maximum inter-cuspal clenching

EMG activity of jaw closing muscles during maximum clenching on a full-arch occlusal splint has been studied many times: the muscle activity has been found to be increased, decreased or unchanged compared to that without a splint.

Wood and Tobias (1984) found a 17% overall increase in the activity of masseter and anterior and posterior temporal muscles when splints (1 and 2.5 *mm* thick) were installed in normal subjects.

Others have found reduced EMG activity in one or more of the jaw closing muscles of TMD patients wearing splints compared to those of TMD patients without wearing splints (Christensen, 1980; Naeije and Hansson, 1991; Kawazoe *et al.*, 1980; Yaffe *et al.*, 1991).

Reduced muscle activity has also been found with anterior teeth bite plane splints (Dahlstrom *et al.*, 1985*a*; Fuchs, 1975; Manns *et al.*, 1989; Wood and Tobias, 1984). Manns *et al.* (1989) showed that during maximum inter-cuspal clenching EMG activity was greatest for bilateral molar splints and full-arch splints, less for bilateral premolar splints and still less for anterior bite plates.

Studies of the effects of splints in normal subjects which found no change in EMG activity during maximum inter-cuspal clenching include those of Dahlstrom and Haraldson (1989) and Kawazoe *et al.* (1980). In addition, MacDonald and Hannam (1984*a* and 1984*b*) did not observe any change in jaw muscle activity of normal subjects except for posterior temporalis when the entire dentition was raised with intercuspal stops (thickness: 1 *mm*). Faulkner *et al.* (1982) did not find changes in the *in vitro* isometric and isotonic contractile properties and fiber types of masseter and temporalis of monkeys which had been wearing splints (20 *mm* thick) for 48 weeks. Dahlstrom and Haraldson (1985) did not find changed EMG activity of TMD patients after wearing splints nightly for 6 weeks.

In a single sample of TMD patients, Holmgren *et al.* (1990) found that EMG activity during maximum clenching increased, decreased or was unchanged after splint therapy. Furthermore, neither immediately nor long-term (6 weeks) wearing of the splint (3.7 *mm* thick) resulted in consistently different EMG activity during maximum clenching on the splint compared to that during maximum inter-cuspal clenching.

Maximum intercuspal clenching activates receptors monitoring the magnitude of the bite force. These receptors may be any combination of (1) Golgi tendon organs (GTO) of jaw closing muscles, (2) periodontal mechano-receptors (PMR), and (3) pressure receptors in the sutures of craniofacial bones (Osborn and Baragar, 1992; Herring and Mucci, 1991). Golgi tendon organs in jaw muscles have only been histologically identified in the cat (Lund *et al.*, 1978). The pressure receptors in craniofacial bone sutures have not been well documented.

Presumably, any combination of the above three receptors must convey the magnitude of the bite force to the central nervous system which could correspondingly adjust its commands to jaw closing motoneurons. However, it is unsettled whether the feedback from PMRs to jaw closing motoneurons is positive (Lavigne *et al.*, 1987; Lund and Lamarre, 1973; Olsson *et al.*, 1988) or negative (Hannam and Matthews, 1969*a*; Orchardson and MacFarlane, 1980; Sessle and Schmitt, 1972; van Steenberghe and de Vries, 1978*b*; van Steenberghe, 1979). Reflex effects from Golgi tendon organs or bone suture pressure receptors have not been described.

2.III.5.b...Postural and nocturnal muscle activities

Many studies have found that splint therapy reduces the postural EMG activity of jaw muscles of some TMD patients; however, postural EMG actually increased in some other patients (Christensen, 1980; Clark *et al.*, 1979; Holmgren *et al.*, 1985 and 1991; Sheikholeslam *et al.*, 1986).

Dahlstrom *et al.* (1985*a*) reported reduced postural activity in anterior and posterior temporal muscles after TMD patients had worn night splints for 1 week. Sessle *et al.* (1990) found a decrease in the postural EMG activity of the superficial masseter and upper and lower heads of the lateral pterygoid: the decrease persisted for about 6 weeks but the activity gradually returned to its original value.

Dahlstrom and Haraldson (1985 and 1989) showed that postural activity was unchanged immediately after splints were installed or after wearing nightly splints for 6 weeks. Clark *et al.* (1979) found that almost half of their patients wearing splints showed either increased or unchanged nocturnal hyperactivity of jaw muscles. In addition, a return of EMG activity to the pretreatment level was noticed in 92%

patients after removing splints. Holmgren *et al.* (1985) found that in patients who wore splints for 15 minutes postural EMG activity increased in 22%, was reduced in 52% and unchanged in 26%.

Sheikholeslam *et al.* (1986) found that postural EMG activity was reduced during 3 - 6 months of wearing splints; however, TMD signs and symptoms returned to pre-treatment levels in 80% of patients within 1 - 4 weeks after stopping the splint therapy.

The nocturnal EMG activity of jaw muscles also appears to respond to full-arch stabilization splint therapy. Clark *et al.* (1979) and Solberg *et al.* (1975) reported reduced nocturnal muscle activity in a majority of bruxing subjects, but the changes were probably not permanent.

Duration of wear and thickness of the splint may both be related to the effectiveness of splint therapy. The effects of the thickness of an occlusal splint on jaw muscles, however, have rarely been examined. Manns *et al.* (1985) found that postural masseter muscle activity was more significantly reduced after three weeks wearing a thick splint (about 4 and 8 *mm* thick) than a thin splint (1 *mm* thick). Temporalis showed an immediate and long-lasting reduction in activity. Major (1988) suggested that continuous wear of a stabilization splint may be more important than its thickness which should be kept minimum.

Although the effectiveness of splint therapy has been thoroughly studied, few have sought to understand how it works. Clark (1984*a*) stated that an occlusal splint alters muscle coactivation patterns, but failed to provide any evidence. Christensen (1980) suggested that a splint may work by stretching jaw muscles beyond their resting length.

Installing an occlusal splint on the upper or lower dental arches is a unique orthopedic procedure. It immediately separates the jaws from their usual resting position and increases the length of the fibers of jaw muscles. Occlusal splint wearers often remove and reinstall splints during a day and, as a results, the tonic activity of jaw closing muscles may be repeatedly increased because when these muscles are lengthened the monosynaptic muscle spindle feedback to the motoneurons supplying these muscles is facilitated. It therefore seems unlikely that this procedure would relax jaw muscles. However, the mandibular rest position may rapidly adapt to changes in vertical occlusal dimension (Goldspink, 1976; Hellsing *et al.*, 1984) and this might be attributed to the addition of sarcomeres in the fibers of jaw closing muscles (Herring *et al.*, 1984) due to passive tension applied by a splint to these muscles. Above all, little is known about how the central nervous system may adjust its commands, possibly through γ motoneurons, in response to the increased muscle length due to the presence of a splint.

2.III.6...MANDIBULAR DYSKINESIA

Dyskinesia includes abnormal movements, such as deviated jaw trajectories and limited range of motion, associated with TMD (Ash, 1986; Bailey *et al.*, 1977;

Clark and Lynn, 1986; Helkimo, 1974; Stohler *et al.*, 1988). It is often attributed to disk displacement, muscle spasm or protected muscle splinting (Ash, 1986; Yemm, 1985).

The general observation seems to be that TMD patients could not perform accurate lateral movements (Clark and Lynn, 1986; Isacsson *et al.*, 1988). The problem is which receptor(s) is responsible for conveying the sense of the position of the mandible: the possible receptors being (1) periodontal mechano-receptors, (2) muscle spindles, and (3) TMJ mechano-receptors. The question seems to be whether the afferent information from any of these receptors in TMD patients is different from that of normal subjects.

Broekhuijsen and van Willigen (1983) concluded that muscle proprioceptors, rather than joint receptors, were responsible for conveying information about mandibular position. Williams *et al.* (1984*a*) found that anesthetizing the periodontal ligaments of maxillary and mandibular central incisors impaired bite force discrimination, while applying anesthesia to the temporomandibular joints did not. In a subsequent study, they showed that the subjects' ability of discriminating bite forces was changed after muscle receptors were impaired by vibratory stimulation of the jaw closing muscles (Williams *et al.*, 1987). Greenfield and Wyke (1966) described mechano-receptors and pain receptors in the capsule of the temporomandibular joint. Its role in detecting mandibular position has been stressed by the following workers (Klineberg *et al.*, 1971; Larsson and Thilander, 1964;

Thilander, 1961). However, joint receptors in TMD patients have rarely been extensively studied.

On the negative side, Hellsing (1980) found that neither muscle vibration nor anesthesia of the periodontal ligaments and/or of the temporomandibular joints affected the ability to produce a given bite force. Furthermore, Dahlstrom *et al.* (1989) showed that perception of joint position was not changed in either TMD patients or normal subjects with joint capsules anesthetized. Stegenga *et al.* (1990) found that both normal subjects and TMD patients (including those with and without joint dysfunction) had difficulty in producing certain predefined bite forces without feedback. This suggested that receptors monitoring the magnitude of bite force in TMD patients were not altered.

Thus, the question of whether or not TMD patients suffer from dyskinesia seems unsettled. Isacsson *et al.* (1988) noted that the often anteriorly dislocated disk could not be the source of altered proprioceptive sensation because the disk was not innervated. Instead, the concomitant displacement of the posterior part of the capsule and the retro-disk tissues pulled forward by the disk, might send incorrect afferent information. An explanation for dyskinesia in TMD subjects seems to rely upon whether the peripheral proprioceptive reception is altered.

CHAPTER 3

MATERIALS AND METHODS

3.I...DEVELOPMENT AND USE OF THE BITE FORCE TRANSDUCER

3.I.1...The housing
3.I.2...The sensors
3.I.3...Strain gauge conditioning
3.I.4...Calibration
3.I.5...Visual feedback
3.I.6...The use
3.I.7...Tasks

3.II...ELECTROMYOGRAPHY, DATA ANALYSIS AND SUBJECTS

3.II.1...Architecture of the muscles under study
3.II.2...Surface EMG apparatuses
3.II.3...Data analysis and statistics
3.II.4...Selection and clinical examination of subjects
  .a...Normal subjects
  .b...TMD subjects

Chapter 3, Section I

DEVELOPMENT AND USE OF THE BITE FORCE TRANSDUCER

It has proved difficult to develop a thin and small bite force transducer capable of measuring the direction of a bite force in the three dimensional (3-D) space. Attempts made to design such a force transducer have not been completely successful as separately indicated Graf *et al.* (1974) and Watanabe and Hannam (1986). As described in 2.I.1., the magnitude of a bite force has most often been measured as its component perpendicular to the occlusal plane. Due to the fact that there was no previous work to follow, the development of the 3-D bite force transducer has involved considerable work in developing various prototypes. The bite force transducer developed for the present project now has a patent pending through the Intellectual and Properties Office of the University of Alberta (Appendix 1).

The objective was to develop a thin bite force transducer and its associated visual feedback system which would allow a subject to "see", on a computer video monitor, the magnitude and direction of the bite force being produced. The force transducer consists of a housing to which sensors are attached. The visual feedback system involved hardware configuration and computer programming.

3.I.1...THE HOUSING

As described in 2.I.2., the directional capability of a bite force transducer largely depends upon the design of its housing. The housing of the bite force transducer used for the studies in this thesis has an **H** shape (Figure 1, *p.* 170). Since excessive jaw separation is not desirable in simulating normal biting, the **H** shape allowed the sensors to be placed on the two vertical plates (Figure 2, *p*. 172). Therefore, the whole transducer, when placed in any position around the dental arch, yielded only a small separation between the upper and lower jaws. Two plastic and one metal model (about 10 times the size of the real force transducer) were made and the metal model was tested (with strain gauges installed).

The material of the housing was made of gauge #20 stainless steel plates (Alex Alloys, Edmonton, Alberta, Canada). If the sensitivity and orientation of the sensor are fixed, stainless steel with lower gauge numbers (thicker and therefore more rigid) reduces the sensitivity of the transducer. Four pieces of the stainless steel were cut or bent into the required shape (Figure 3, *p*. 174). They were then welded to form the hollow **H**-shaped cross section. The above procedures were completed in the Technical Services Machine Shop. The distance between upper and lower surfaces of the cross bar of the **H** is 2 *mm* (Figure 4, *p*. 176). The remaining dimensions of the housing (considered the same as those of the whole transducer) were $25\times15\times17^3$ *mm* (*length×width×height*) and are shown in Figure 4 (*p*. 176).

3.I.2...THE SENSORS

Bonded strain gauges were selected as the sensors for the force transducer. All the strain gauges were supplied by Micro-Measurements Inc. (Raleigh, North Carolina, USA).

Out of numerous types of strain gauges, four identical strain single gauges (CEA-13-062UW-350) were first chosen. The four strain gauges were installed upright on the two vertical surfaces of the **H** shaped housing; two gauges on the same plate were parallel to each other and separated by about 8 *mm* (Figure 5, *p*. 178). The four-channel strain gauge outputs were fed into a strain gauge conditioner (Model 2100, Vishey Instruments, Raleigh, USA). After considerable time spent testing this configuration of sensors, it was found that the four vertical gauge configuration was excellent for distinguishing changing (calibration) force directions of in the frontal plane (from side to side) but not sufficiently sensitive for those in the sagittal plane (from anterior to posterior) (Figure 5). Therefore, this configuration was abandoned. The insensitivity in the sagittal plane may be attributed to the fact that the two vertically oriented strain gauges on the same plate were too close to each other to detect differences in changing force directions in the sagittal plane. Nonetheless, time was not totally wasted because a close linear relationship was confirmed between the applied calibration forces (standard loads) and the strain outputs from any of the four gauges in each of the tested directions.

Stacked strain gauge rosettes were then used. Three single strain gauges (gauge factor of 2.05 at 24°C) are combined into a rosette in the factory. The rectangular rosette (WK-06-060WR-350) used for the present study contained three strain gauges each of which was separately by 45°. The rosettes operate in the temperature range of -269° to +290°C. Other technical specifications of this rosette are provided in Appendix #2. After the surface of the housing was prepared, a rosette was installed outside each vertical plate of the **H** (Figure 2 - *p*. 172). The installed rosettes were tested with voltmeter and megohm-meter to detect any deterioration or leakage of current when installation was completed. Finally the rosettes were coated with two layers of adhesive: (1) M-Coat A, Polyurethane coating and (2) moisture-proof glue (M-Bond AE-10/15). The upper temperature range for the adhesives was 140°C. The complete customized strain gauge installation procedures can be found in Appendix #3.

After two rosettes were successfully installed for a transducer, a parallel computer cable (25 pin and about 1.5 *m* long) was made containing six leads from the six strain gauges of the two rosettes and connected to the strain gauge conditioning system.

3.I.3...STRAIN GAUGE CONDITIONING

Unless otherwise stated, all the strain gauge conditioning facilities described in this section were supplied by Sciemetric Instruments Inc. (Nepean, Ontario, Canada). The six strain gauges contained in two rosettes for a force transducer were connected via a parallel computer cable to a Model 84 Strain Gauge Conditioner card. The Model 84 card provides each strain gauge with a Wheatstone bridge circuit configured in 1/4 bridge setup (Figure 6, *p*. 180). The 1/4 configuration makes every gauge in the transducer active and yield its own strain output when stressed (Dally and Riley, 1978; Perry and Listner, 1964). An excitation voltage of 3 *V* was supplied to each gauge (channel). For the safety of human experimentation, the excitation voltage and current were derived from a rechargeable battery (12 *V* and 26 *A/hr.*, Model PS 12260, Power-Sonic Corp., Redwood City, California, USA). The battery was regularly charged with a charger (Motomaster 11-1561, Canadian Tire, Edmonton, Alberta, Canada).

The conditioned strain gauge signal from the Model 84 card was fed to an analog/digital converter card (Model 233) and an IBM computer interface card (Model 802). The digitized strain gauge data were originally recorded at 1 *Hz* onto the hard disk of an IBM XT computer. Later, an IBM compatible 386/25*MHz* computer (with mathematic co-processor) replaced the IBM XT and increased the sampling frequency to 10 *Hz*. The computer software used to operate strain gauge conditioning was *Quicklog* (Version 2.01).

3.I.4...THE CALIBRATION

The calibration system is shown in Figure 7 (*p*. 182). A metal camera tripod was used as the base for holding the force transducer. Thin layers of quick-set acrylic (Dura Lay, Dental Mfg. Co, Worth, Illinois, USA) were placed in the upper and lower recesses of the **H**. Before the acrylic was set, a bolt was placed in the center of the lower acrylic block and a small hole, for location purposes, was put in the center of the upper acrylic block. After both pieces of the acrylic became solid, the whole transducer was screwed onto the camera tripod. A pin held by a vice served as the pointer (down to the hole in the center of the upper acrylic block) through which standard loads were applied. Applying calibration forces through the pin was assumed to have nearly the same effects as applying calibration forces through a tooth. The basis for such assumption is the widely-accepted Saint-Venant's principle in strain and stress analysis which states that a system of forces acting over a small region of boundary can be replaced by a statically equivalent system of forces without introducing appreciable changes in the distribution of stresses in regions well removed from the area of load application (Dally and Riley, 1965).

The standard loads used to apply forces were brass weights from 10 *N* to 150 *N*. The directions of the forces applied as loads were 0°, 15° and 30° away from the vertical (to the ground) at 45° intervals around the full 360° in the horizontal plane. A change in the direction of force was made possible by changing the angle of the head of the tripod. When a load was applied to the cross bar of the **H**, the vertical plates of the **H** were deformed along with the strain gauges bonded to them. The change in resistance of each strain gauge is proportional to the change in length in the long axis due to deformation (Dally and Riley, 1978).

The principal strains were calculated following the equation recommended by Dally and Riley (1978). By comparing the magnitude of changes in the output from the six gauges it was possible to formulate equations which would predict the magnitude and the direction in the sagittal and frontal planes of a load with unknown direction. For instance, by comparing the changes in resistance of the two anterior gauges (left and right) with those of the two posterior gauges, the direction of the force in the sagittal plane could be calculated. By comparing the differences between the left and right gauges the direction of the force in the frontal plane could be calculated. A set of standard calibration procedures is provided as Item 4 in Appendices. The accuracy and margins of error of the force transducers used for the present study are shown in Table 5 (*p.* 167). For instance, if outside the mouth the transducer was subjected to a known load up to 150 *N* in a known direction, the parameters predicted by the equations were within ± 5 *N*, and about ± 2° in an antero-posterior direction and ± 4° medio-laterally of the true parameters.

3.I.5...VISUAL FEEDBACK

The magnitude and direction of a bite force were displayed graphically on the video monitor of the computer used for recording the bite force signal (Figure 8, *p.* 184). Initially, the information about a bite force was programmed to be displayed in three dimensions on the computer screen. Later, it was found that the 3-D display was confusing to subjects compared to a two dimensional display and thus the latter was adopted. Subjects were therefore provided with the real-time visual feedback of the magnitude and direction of the bite force they were producing. The signal delay was minimal.

When the transducer was placed in the mouth so that its horizontal cross was parallel to the upper occlusal plane, a subject was asked to produce a bite force of about 200 *N* at an angle of 5° anterior from the vertical in the sagittal plane and 15° to the right of vertical in the frontal plane on the left first molar tooth. The magnitude and direction of this bite force is displayed on the computer screen as in Figure 8.

Three large concentric circles, divided into quadrants by a cross (Figure 8), served as a map which displayed the direction of the bite force. The center of the cross represented a vertical bite force. The four arms of the cross represented medial, lateral, backward and forward directions. The three concentric circles showed angles of 10°, 20° and 30° away from the vertical. A smaller empty circle (*the target circle*) was programmed to appear on the screen in the position which corresponded with the required direction of the bite force predefined by the operator (5° forward and 15° right in Figure 8). The actual direction of the bite force being produced by the subject was displayed as a blinking solid circle. The magnitude of the bite force was displayed on a vertical scale. The scale can be infinitely varied. In practice, ranges from 100 *N* to 1,000 *N* have been used. Either the magnitude or the direction of a bite force can be hidden when necessary. The objective of the subject was to maintain a bite force of the required magnitude (on the force scale) with the blinking red dot in the center of the fixed empty *target circle*.

The blinking solid circle indicating the direction of a subject's bite force usually flickered in and around a target. Some of this variability was probably real but some of it was related to excessive sensitivity of the system. During calibration with a stable load the circle flickered over an area representing a few degrees of movement.

The six columns of numbers at the bottom of Figure 8 monitored the strain values (in microstrains) recorded by each strain gauge. They were continually scrolling and served to reassure the operator that the two rosettes were producing appropriate strain values.

3.I.6...THE USE

Compared to development of the force transducer, the application of the transducer was straightforward. The transducer was sterilized for four hours in ethylene oxide each time before use with a new subject.

Thin layers of quick set acrylic (Dura Lay, Dental Mfg. Co, Worth, Illinois, USA) were placed in the upper and lower recesses of the **H** and the subject bit into them until the cross bars were encountered. When the acrylic was set the transducer was removed and the upper and lower acrylic blocks were trimmed, when necessary, so that they surrounded only the occlusal surface of one pair of upper and lower teeth (Figure 9, *p.* 186). The acrylic provided a stable and, more importantly, reproducible base for the upper and lower occluding teeth in the upper and lower recesses between the vertical arms of the **H** after the transducer was reinstalled. After the bite force transducer was installed between the upper and lower first molars, the jaw separation measured as the inter-incisal distance was 4 to 6 *mm* (Figure 9, *p*. 186).

Outputs from the six individual strain gauges were fed into the strain gauge conditioning equipment as described in 3.I.3. The bite force measurement flow diagram is shown as Figure 10 (*p*. 188).

Lewis and Yemm (1983) indicated that the ability of the human subject to use the jaw closing muscles in target tracking was dependent upon the magnitude of the force: the greater the effort demanded, the greater the error. However, they only studied the range of isometric bite forces up to 4 *kg*. The findings in this thesis have been different in that the greater the bite force (e.g. 30 *kg* compared to 5 *kg*), the more stable the direction of a bite force. This agrees with Lindauer *et al*. (1991) who indirectly suggested that the linear correlation coefficients of the EMG activity of jaw muscles became better at higher bite force levels.

3.I.7...TASKS

For normal subjects, a wide range of predefined magnitudes and directions of bite force was used as tasks. The magnitude of bite forces investigated was from 50 *N* to 300 *N* in 50 *N* increments; the directions were vertical, and 20° forward, backward, medial, and lateral in 90° intervals in the horizontal plane. Two separate experimental sessions were conducted with each subject whenever possible: one for the left side tasks and one for the right. If, after several attempts, a subject was not able to perform a specific task he/she was instructed to abandon it. The sequence of tasks was randomly assigned. The interval between two tasks was between 2 and 5 minutes. This allowed the subjects to relax their muscles. Each left or right session required 2 - 3 hours depending upon the ability of a subject to perform bite force tasks.

TMD patients were unable to complete the wide range of bite force tasks as normal subjects did. They usually suffered discomfort after about 10 tasks including unsuccessful ones. Hence, only a limited range of data could be obtained from TMD patients. The directions used as tasks were the same as those used for normal subjects but with a limited range being any of the vertical, and 20° forward, backward, medial, and lateral in 90° intervals in the horizontal plane. The magnitude of the bite force was chosen to be the one which was well within the capabilities of the subject.

Chapter 3, Section II

ELECTROMYOGRAPHY, DATA ANALYSIS AND SUBJECTS

3.II.1...ARCHITECTURE OF THE MUSCLES STUDIED UNDER STUDY

Masseter and temporalis were studied with surface electromyography (EMG) in the present study. The structure of these two muscles is briefly described below in this section. These two muscles, along with medial and lateral pterygoids, belong to a group usually referred to as muscles of mastication or masticatory muscles. The jaw muscles are often used as a synonym for jaw closing muscles, but may include others such as lateral pterygoid and suprahyoid muscles (*e.g.* digastric, mylohyoid, *etc.*). *Gray's Anatomy* (edited by Williams and Warwick, 1980) is used as the major source of reference.

The masseter is quadrilateral, and consists of three superimposed layers blending anteriorly. It is usually described as having two or three parts: the superficial, (middle) and deep. *The superficial layer*, being the largest, arises by a thick aponeurosis from the zygomatic process of the maxilla, and from the anterior 2/3 of the lower border of the zygomatic arch; its fibers pass downwards and backwards, to be inserted into the angle and lower half of the lateral surface of the ramus. *The middle layer* arises from the deep surface of the anterior 2/3 of the zygomatic arch and from the lower border of the posterior 1/3 and is inserted into the middle of the ramus of the mandible. *The deep layer* arises from the deep surface of the zygomatic arch and is inserted into the upper part of the ramus of the mandible. In most people, the superficial masseter can be palpated as an oblique mass passing from the cheek bone to the angle of mandible when a subject is clenching the teeth.

The temporalis is fan-shaped and arises from the whole of the temporal fossa and from the deep surface of the temporal fascia. Its fibers converge and descend into a tendon which passes through the gap between the zygomatic arch and the side of the skull, to be attached to the medial surface, apex, anterior and posterior borders of the coronoid process, and the anterior border of the ramus of the mandible nearly as far as the last molar tooth.

Both the masseter and temporalis are innervated by the mandibular division of the trigeminal nerve which also conveys proprioceptors arising from them (afferents from muscle spindles, and Golgi tendon organs if any).

In this study, the superficial masseter and the anterior temporalis were examined with EMG. With the upper and lower jaws closed or at the mandibular rest position, the resultant line of action of the superficial masseter is directed obliquely upward and forward, while that of the anterior temporalis is nearly vertical.

These two muscles were palpated and identified with markers. The skin over them was rubbed with an alcohol pad. Male subjects were asked to shave the areas of electrode placement before experiments.

3.II.2...SURFACE EMG APPARATUSES

Bipolar surface electrodes (9 *mm* sensor diameter) filled with electrode paste were installed with sticky collars over the left and right superficial masseter and anterior temporal muscles. All the above items (the electrodes, the conducting paste and the collars) were supplied by Beckman Instruments, Inc., Anaheim, California, USA. Each pair of the electrodes was placed parallel to longitudinal axis of the muscle. This orientation is known to record a greater muscle potential than placing electrodes transverse to the longitudinal axis of the muscle (Ahlgren and Henrikson, 1987). In this study, the electrodes were 25 *mm* apart. Position of electrodes can be found in Appendix Figure 2 (*p*. 289) in Appendices Item 4. A reference electrode was placed on the skin over the fifth cervical vertebra.

The 4-channel EMG signals of the bilateral masseter and temporal muscles were amplified with preamplifiers (P15, Grass Medical Instruments, Quincy, USA) at a gain of 1,000 and with a bandwidth of 10 - 1,000 *Hz*. The low cut-off frequency was set at 10 *Hz* for future fast Fourier transform analysis. Occasionally, this low cut-off frequency was increased to 100 *Hz* due to 60 *Hz* AC contamination in the EMG signal. In this case, the file was correspondingly marked.

The raw EMG signals were displayed on an 8-channel oscilloscope (5A14N, Tektronix, Beaverton, USA) and fed through a 12-*bit* analog/digital converter at 1,000 *Hz*/per channel (Dash-8, Mytrabytes Ltd., Wilminton, USA). Finally the digitized data were picked up by the data acquisition board (also Dash-8) installed in a personal computer (IBM compatible 486/33 *MHz* with a mathematic co-processor) and collected onto its hard disk (120 *Megabytes*). Recording duration for each task was 4.096 seconds (This unusual time was chosen for Fourier Transform analysis). Figure 11 (*p*. 190) provides a flow chart of EMG recording devices.

3.II.3...DATA ANALYSIS AND STATISTICS

The digitized integrated EMG data, collected through a commercial software (the *Labtech Notebook*, Mytrabytes Ltd., Wilminton, USA), were in ASCII format. There were 16,384 data points in each file (4.096×1000×4: recording duration × sampling rate × the number of channels). If a subject succeeded in performing all the bite force tasks, there were 30 files (6×5: magnitudes of bite force in each direction × the total number of bite force directions studied) plus the maximum voluntary contraction files. These files were normalized by the following methods with custom developed computer software. It is obvious that the data analysis was time consuming.

(1) Full-wave rectification: this turned all the negative components of the AC EMG signal upwards to become positive.

(2) Averaging (smoothing): the rectified EMG data points were averaged over 100 data point intervals and, hence, an integrated EMG for each muscle was obtained. Figure 12 (*p*. 192) provides three diagrams showing raw, full-wave rectified and integrated EMGs. During an experiment, the EMG traces were checked

regularly on the oscilloscope and as a graphical presentation of a recorded file (Figure 13, *p*. 194).

(3) Obtaining MVC: this involved a way to identify the maximum voluntary contraction (MVC) of a muscle. MVC is a controversial value and may never actually be obtained during several contractions, especially for a group of synergistic muscles. MVC was obtained for each muscle by requesting a subject to bite on the transducer, for about four seconds, as hard as possible, while the direction of the bite force was ignored (hidden from subjects). The procedure was repeated three times. The three EMG files were later full-wave rectified and averaged following the above methods. The average of the top 200 values in each file was calculated. Finally, the greatest of the three averaged values was considered as the MVC for a muscle. Literally, this may still not be the maximum EMG which can be recorded in a muscle when it (or its innervating motor nerve) is supramaximally stimulated. It became, however, an arbitrary value (which may be very close to the MVC) against which all other EMG records were measured.

(4) Normalization of EMG: all remaining EMG records were calculated as percentages of the MVC values for the corresponding muscles. Hence, relative EMG units were used.

(5) Ratios of paired muscles: muscles were grouped into pairs (such as the working side temporalis and the working side masseter) and ratios of their normalized EMG activities were calculated.

GraphPad Instat (GraphPAD Software, San Diego, California, USA) was used for all the statistical analyses. Linear correlation analysis was applied to the normalized EMG data points plotted against bite force increments (from 50 to 300 *N*) in each of bite force directions (3.I.7.). EMG activity was measured when the bite force tasks were produced on the left and right side of the jaw. The linear correlation coefficients (*r* values) were calculated.

Lindauer *et al.* (1991) tested the reproducibility of surface EMG recording in superficial masseter and anterior temporal muscles when the same magnitudes of bite forces were produced in two separate sessions. They concluded that the slope of an EMG-bite force plot (not the y-intercept) was reproducible.

One-way analysis of variance (*ANOVA*) was used to test any differences among the ratios of the paired muscles when producing bite forces in each of the performed directions of bite force. The Bonferroni method was used to compare ratios of paired jaw muscle activities for any of the two different directions of bite force. P values of greater than .05 were rejected; $.05 > p > .01$ were considered significant; and values $p < .001$ extremely significant.

3.II.4...SELECTION AND CLINICAL EXAMINATION OF SUBJECTS

Normal subjects refer to those, when examined, who did not have and had never had TMD symptoms or signs. TMD subjects (patients) were those who, at the time of the experiment, had at least one sign of temporomandibular disorders (TMD).

3.II.4.a...Normal subjects

Normal subjects (those without TMD) were randomly recruited from dental and graduate students. The criteria used for selecting normal subjects included: (1) generally good health and not on any medication; (2) no present or previous history of jaw muscle pathology or temporomandibular joint disorders; (3) no periodontal disease or gingivitis; (4) no facial asymmetry; (5) no unilateral chewing habit; (6) no malocclusion (Angle's Class I occlusion was required).

Following these standards five students participated in this study: two males and three females. Their age ranged from 21 to 29 years. Subjects were briefly informed about the objectives of the study and given the option to participate. They were assured that the project had been approved by the Human Ethics Committee of the Faculty of Dentistry. All subjects were given the right to withdraw at any stage of the experiment. The agreed consent forms were signed (Appendices Item 5).

On the day of experimentation, a subject sat upright with a head rest on a dental chair. Jaw muscles and the temporomandibular joint areas were examined to detect any tenderness or pain. Intra-oral examination mainly recorded problems such as missing teeth, caries, fillings and periodontal disease, *etc.*

During an experiment, a subject was advised to abandon a task which seemed too difficult to perform after 3 trials. Measurements for the left and right sides of the jaw were carried out on different days for three subjects (two males and one female). Only one set of measurements was done with the other two subjects.

3.II.4.b...TMD subjects

All the TMD subjects were recruited from patients treated at the Temporomandibular Joint Investigation Unit at the Faculty of Dentistry. Patients were first selected by clinical impression and a review of the cases and suitable patients were then informed about the objectives of the studies and the time commitment. Written consent form (Appendices Item 6) were signed.

On the day of experiment, a patient was examined separately by two clinicians who both followed the Craniomandibular Examination Index proposed by Fricton and Schiffman (1986, 1987). The examination sheet is attached in Appendices Item #7. After clinical examination the TMD subject was guided to the laboratory and sat upright on a dental chair with head rest.

It was soon found that TMD subjects were unable to perform nearly as many tasks as normal subjects. Either slight or substantial pain, usually arising from one of the jaw muscles or the temporomandibular joints, appeared during the experiment. Patients were constantly advised that they could terminate the experiment at any time.

CHAPTER 4

RESULTS

4.I...CO-ACTIVATION PATTERNS OF NORMAL JAW MUSCLES

4.I.1...Production of the bite force tasks...95
4.I.2...Dispersion of the EMG data...96
4.I.3...Bite force-EMG relationship...97
4.I.4...Mirror image muscle patterns for left and right tasks...99
4.I.5...Muscle tensions with regard to bite force directions...100
    .a...Tensions as groups...101
    .b...Individual muscle tensions...102
        .(1)...In the sagittal plane...102
        .(2)...In the frontal plane...103
4.I.6...Ratios of muscle pairs...104
    .a...Sagittal plane: ratios for force directions...104
    .b...Frontal plane: ratios for force directions...105
    .c...The ratios for force directions in 3-D...106

4.II...BEHAVIOR OF JAW MUSCLES OF TMD SUBJECTS

4.II.1...Case I
    .a...Clinical examination
    .b...EMG muscle patterns
4.II.2...Case II
    .a...Clinical examination
    .b...EMG muscle patterns
4.II.3...Case III
    .a...Clinical examination
    .b...EMG muscle patterns
4.II.4...Case IV
    .a...Clinical examination
    .b...EMG muscle patterns
4.II.5...Case V
    .a...Clinical examination
    .b...EMG muscle patterns
4.II.6...Case VI
    .a...Clinical examination
    .b...EMG muscle patterns

Chapter 4, Section I

CO-ACTIVATION PATTERNS OF NORMAL JAW MUSCLES

4.I.1...PRODUCTION OF BITE FORCES

When all the subjects initially faced the feedback of their bite forces, most of them had some degree of difficulty producing a bite force specified precisely by the target on the computer screen. They usually practised for 10 to 15 minutes before being able to perform most required tasks effectively. During experiments some subjects were still not able to perform the whole range of bite force magnitudes in some specified directions. For example, a subject could produce backward bite forces from 100 *N* to 250 *N* but could not reach 300 *N*. When this occurred, a subject was instructed to abandon the 300 *N* task. Occasionally a subject was not able to produce any force of a specified direction and this happened most often with lateral bite forces (described below).

As long as a subject got used to the bite force feedback, the magnitude and direction of a bite force were usually well produced and maintained. The actual direction of the bite force, however, did fluctuate (sometimes very dramatically). Whenever the fluctuation of the bite force direction was more than 10 degrees away in any direction, the recording (computer file) was abandoned and the subject was requested to repeat the same task. The magnitude of a bite force was usually better maintained than its direction; any fluctuation greater than ± 50 *N* was rejected.

Occasionally subjects complained about 'tiredness' or 'fatigue' in their jaw muscles. When this occurred, it was usually near the end of an experiment. Such perception may indicate early signs of muscular fatigue at submaximal contraction levels (as the magnitude of bite forces used as tasks in the present study was within submaximal contraction levels in most cases). Whenever this happened, even though physiological fatigue did not seem to have occurred, the bite force transducer was removed from the subject for 5 or more minutes for two reasons: (1) recovery from the submaximal fatigue is relatively long (more than 1 minute as compared to the maximal fatigue); and (2) feelings about 'fatigue' may prevent a subject, psychologically, from performing further bite force tasks. The experiment was not resumed until the feeling of 'tiredness' or 'fatigue' disappeared. None of the normal subjects reported any pain associated with the experiment.

4.I.2...DISPERSION OF EMG DATA

Figure 14 (*p*. 196) shows the dispersion of the normalized EMG data points in all subjects. The combination of the muscles and tasks for each plot was randomly chosen: (1) the balancing masseter during producing vertical bite forces; (2) the balancing temporalis during exerting 20° backward bite forces; (3) the working masseter for 20° medial bite forces and (4) the working temporalis during performing 20° forward bite forces. Data points representing percentages of EMG_{max} for all subjects were plotted against bite force increments. A linear regression line was fitted for all the data points (in each plot) for one muscle during performing a particular task.

Most data points showed some scatter within a reasonable distance from the linear regression lines fitting all the data points in each plots. Most, but not all, of the EMG data points which were outliers were found at higher force levels (beyond 100 *N*); working temporalis was an exception (Figure 14D). These outlying data points included those of (1) the balancing masseters of three subjects when biting vertically (symbolized as solid and open squares and solid triangles in Figure 14A); (2) the balancing temporalis of one subject during producing 20° backward bite forces (symbolized as solid triangles in Figure 14C); and (3) the working temporalis of one subject upon exerting 20° forward bites (symbolized as solid squares in Figure 14D).

4.I.3...BITE FORCE-EMG RELATIONSHIP

This relation was expressed as the averaged surface EMG activity of the four jaw muscles in all the subjects plotted against graded bite forces in all the studied directions. There were two ways to examine this issue: (1) to calculate regression lines for averaged muscle tensions against incremental bite forces in each direction in the sagittal and frontal planes for all the subjects (Figures 15 and 16 respectively, *pp*. 198,200) and (2) to calculate correlation coefficients (*r* values) for regression lines for the muscle activity in single individuals against incremental bite forces. For every bite force direction *r* values for all the subjects were plotted (Figures 17 to 21, *pp*. 202-210).

In most cases, linear regression lines fitted well with most sets of the averaged percentage EMG data points for all the subjects when producing bite forces projected in the sagittal and frontal planes (Figures 15 and 16 respectively). All the linear regression lines were significantly different from zero ($0.01 > p > 0.001$) except for those between lateral bite forces and EMG activities of balancing temporalis ($p=0.18$) and working masseter ($p=0.17$). There seemed to be a roughly linear relationship between the integrated and normalized EMG activity of the four studied muscles and the graded bite forces of different directions except the above two cases. A change in the direction of a bite force did not appear to alter the linearity between the EMG activity of jaw muscles and the magnitude of the force. In other words, the linearity did not seem to be specific to a particular bite force direction.

In Figures 17 to 21, the different numbers of bars representing r values were due to some subjects only being able to produce one or two magnitudes of bite forces in some directions or some subjects not being able to produce any force in a direction (*e.g.* only three subjects were able to produce lateral bite forces for 50 *N*, 100 *N*, and 150 *N*). The majority (94%) of the correlation coefficients (r values) were greater than 0.75 (Figures 17 to 21); only 4 out of 72 (6%) were below 0.75. The range of all the r values was from 0.28 to 0.99 with an average of 0.87 and a standard deviation of 0.17. Muscles and tasks with r values less than 0.50 were (1) $r = 0.28$: for the balancing masseter of one subject during producing 20° lateral bite forces (Figure 19); (2) $r = 0.36$: for the balancing masseter of one subject during producing 20° forward bite forces (Figure 17); and (3) $r = 0.49$: for the working masseter of one subject during producing 20° backward bite forces (Figure 18). Medial and vertical bite forces yielded r values closer to 1 than the other forces. Table 6 (*p*. 168) shows the average r values and corresponding standard deviations for each of the five bite force directions for all the subjects along with the overall mean and standard deviation.

All regression lines were expressed as equations of the form $Y = mX + c$. The average of the slope (m) was 0.18 with a standard deviation of 0.06 and the average of the Y intercept was 3.72 with a standard deviation of 4.11. The averaged Y intercept (c) was fairly close to the origin of the coordinate system. Figures 15 and 16 also showed that the regression lines passed close to the origin.

4.I.4...MIRROR IMAGE MUSCLE PATTERNS FOR LEFT AND RIGHT TASKS

The EMG data points (percentages of EMG_{max}) were pooled for a given muscle undertaking a given task. Separating left and right sides, the pooled results were plotted against bite force increments for each direction (Figure 22, *p*. 212). A muscle on the working side for one half of the experiments was on the balancing side for the other half.

The averaged muscle tensions for the equivalent bite force (direction) tasks performed separately on the left and right sides were plotted for each of the studied bite force directions. This left and right comparison was used to (1) evaluate whether equivalent bite force tasks on the left and right side of the jaw (targets of identical magnitudes and directions) would yield similar muscle activity patterns and (2) assess the accuracy of the bite force transducer and EMG measurements.

There was very good agreement between the regression lines representing EMG activity of the four muscles for producing left and right side bite forces parallel to the sagittal plane: the vertical, 20° forward and backward bite forces having mirror image EMG activity between the left and right muscle patterns (Figure 22A & A', B & B', C & C', *p*. 212). Although the working temporalis on the left side showed somewhat higher activity when producing the 20° backward bite forces (Figure 22B), the pattern of muscle activity for this direction was the same as that on the right side (Figure 22B, *p*. 212).

The agreement for bite forces in the frontal plane (medial, vertical and lateral) was only moderately good. The patterns of muscle activity for producing 20° medial bite forces were different (Figure 22D & D', *p*. 212). However, a more important point seemed to be that all the muscles contracted roughly to the same degree and it seems worthless to distinguish these muscle tensions. The closeness of muscle tensions for all the four muscles was also true for vertical bite forces (Figure 22C & C', *p*. 212). Note, however, that the patterns of muscle activity for producing medial and vertical bite forces were different even though all the muscles were closely activated in both cases. The left and right muscle patterns for the lateral bites showed on moderate agreement (Figure 22E & E', *p*. 212). The working masseter on the left side was more dramatically activated as the magnitude of the bite force increased from 50 *N* to 150 *N* (Figure 22E, *p*. 212).

4.I.5...MUSCLE TENSION WITH REGARD TO BITE FORCE DIRECTIONS

Figure 23 (*p*. 214) shows the averaged muscle tensions (combined left and right side EMG data points) for all subjects during producing bite forces of different directions. EMG activity of each of the four muscles was also plotted against altered directions of bite forces in the sagittal plane (Figure 24, *p*. 216) and the frontal plane (Figure 25, *p*. 218).

4.I.5.a...Tensions as a group

For the 20° forward bite forces (Figure 23A, *p*. 214), the working masseter was the most active muscle, and the balancing temporalis was least active. The balancing masseter and working temporalis were equally activated.

The working temporalis was the most active muscle for the 20° backward bite forces followed by the balancing temporalis (Figure 23C, *p*. 214). The working and balancing masseters showed less activity.

For both the vertical and 20° medial bite forces (Figure 23B or 23B' and 23D respectively, *p*. 214), all the four muscles contracted to approximately the same degree. It seems that balancing side muscles were more active than the working side ones for producing 20° medial bite forces (Figure 23D, *p*. 214), while the reverse was true for producing vertical bite forces (Figure 23B or B', *p*. 214). Therefore, even though all the four muscles were closely activated in both cases, the patterns of muscle activity were probably different.

The working temporalis was consistently the most active muscle for producing 20° lateral bite forces and it was followed by the working masseter. The activity of balancing masseter seemed to be very strong for 50 *N* but its activity increased little as the force increased (Figure 23E, *p*. 214).

When the direction of a bite force changed from the 20° forward to vertical to 20° backward in the sagittal plane (Figure 23A,B,C, *p*. 214), the following muscle activity patterns were found: (1) bilateral masseter muscles were more active than bilateral temporal muscles for the 20° forward bite forces; (2) the activity of bilateral temporal muscles seemed to slightly exceed that of the masseters for the vertical bite forces and greatly exceeded that of the masseters for the 20° backward bite forces.

Changing bite force directions from 20° medial to vertical in the frontal plane (Figure 23D,B') gave rise to only slightly varied muscle activity between the four muscles. A further tilt of the bite force to the 20° lateral (Figure 23E, *p*. 214), however, caused greatly varied muscle patterns. The activity of the working side muscles seemed to slightly exceed that of the balancing for the vertical bite forces and greatly exceeded that of the balancing for the 20° lateral bite forces. The lateral bite forces were the most difficult to produce; none of the subjects was able to produce a lateral bite force greater than 150 *N*.

4.I.5.b...Individual muscle tensions

Patterns of activity for individual muscles were evaluated by plotting the changes in the tension of a muscle for altered bite force directions projected separately in the sagittal and frontal planes.

4.I.5.b.(1)...In the sagittal plane

As a general trend, the working side muscles were more active than balancing side muscles.

Both the working and balancing temporal muscles showed gradually increased activity as the direction of bite forces changed from 20° forward to backward and reached greatest activity when biting vertically (Figure 24A,B, *p*. 216). Note that the working temporalis was more active for 20° backward bite forces at lower force levels (< about 125 *N*) and more active for vertical bite forces as the magnitude increased (Figure 24A, *p*. 216).

As the bite forces were tilted from 20° forward to backward (through vertical), the working masseter demonstrated gradually decreased activity (Figure 24C, *p*. 216). The balancing masseter showed gradually decreased activity when the bite force changed from vertical and 20° forward to backward; it was more active for 20° forward bite forces up to about 140 *N* and was then more active for vertical bite forces.

4.I.5.b.(2)...In the frontal plane

The working temporal and masseter muscles both showed increasing activity as the bite force changed from 20° medial to lateral (via the vertical) (Figure 25A,C, *p*. 218). The working masseter was rather inactive for a 20° medial bite force below 100 *N* and its activity dramatically increased for those medial forces above 100 *N*. Both the balancing temporal and masseter muscles showed little variation in their activity when the bite forces changed from 20° medial to lateral (via the vertical).

4.I.6...RATIOS OF MUSCLE PAIRS

A ratio for a muscle pair was obtained by averaging all the ratios of this muscle pair for producing incremental magnitudes of a bite force in a particular direction. The averaged ratios of the following four pairs of muscles were examined separately in the sagittal and frontal planes: (1) the working temporalis over the working masseter; (2) the balancing temporalis over the balancing masseter; (3) the working temporalis over the balancing temporalis; (4) the working masseter over the balancing masseter. Therefore, 12 ratios (4 muscles pairs × 3 bite force directions) were examined in each of the sagittal (Figure 26, *p*. 220) and frontal (Figure 27, *p*. 222) planes.

The majority of the percentage EMG activity ratios of the paired muscles were constant with fairly small standard deviations. In most cases, ratios were also constant for fixed directions of the bite force, regardless of the magnitude of the bite force.

4.I.6.a...The sagittal plane: ratios for changing directions

For the ratio of the working temporalis and working masseter (Figure 26A, *p*. 220), extremely significant differences ($p < 0.001$) were found when the bite forces changed from 20° forward (four left bars) to 20° backward (four right bars). For the forward bite, the working masseter was more active than the working temporalis; the reverse was true for vertical and backward bites.

The ratios of balancing temporalis and balancing masseter (Figure 26B, *p*.220) also showed significant differences ($p < 0.001$) for changing bite forces from 20° forward to 20° backward. The quantitative ratios were, however, different from their working counterparts. The balancing masseter was more active than the balancing temporalis for all the three bite force directions in this plane when compared to their working side pairs.

The working and balancing temporal muscles yielded an uneven change in the ratios (Figure 26C, *p*. 220). The 20° forward bite forces produced an averaged ratio which was significantly ($p < 0.001$) different from those of vertical and 20° backward bite forces, between which the ratios were not significantly different.

For the ratio of working over balancing masseters (Figure 26D, *p*. 220) 20° backward bite forces yielded significantly different ($p < 0.001$) ratios from those for

20° forward and vertical bite forces, between which the ratios were not significantly different.

4.I.6.b...The frontal plane: ratios for changing directions

The difference between the ratios of working temporalis to working masseter (Figure 27A, *p*. 222) was extremely significant ($p < 0.001$) between 20° lateral and 20° medial and vertical bites. Ratios between 20° medial and vertical bites were not significantly different.

The same pattern was found for the ratio of balancing temporalis and balancing masseter (Figure 27B, *p*. 222). This ratio for the lateral bites was different from the vertical and 20° medial bites. The ratios of vertical and 20° medial bites were not significantly different from each other.

The difference between the ratios of working temporalis to balancing temporalis (Figure 27C, *p*. 222) was extremely significant ($p < 0.001$) between the 20° lateral and vertical or 20° medial forces. The ratios between the vertical and 20° medial bites were significantly different ($p < 0.05$).

The difference between the ratios of working masseter to balancing masseter (Figure 27D, *p*. 222) was extremely different ($p < 0.001$) for 20° lateral bites from those for vertical and 20° medial bites. Vertical and 20° medial bites did not yield significantly different ratios.

4.I.6.c...The ratios for changing directions in 3-D

Figure 28 (*p*. 224) provides all the ratios in both the sagittal and frontal planes.

For changing bite force directions projected in the sagittal plane, muscle pairs on the same side (*i.e.* temporalis over masseter on either the working or balancing side) nearly always produced statistically different ratios for different bite force directions (Figure 28A,B, *p*. 224). Bilateral muscle pairs were less distinctive (Figure 28C,D, *p*. 224).

For changing force directions in the frontal plane, bilateral muscle pairs (*i.e.* working and balancing temporal muscles; working and balancing masseters) produced little difference between the ratios for the medial and vertical bite forces (Figure 28C',D', *p*. 224). All the differences between, however, the ratios for the vertical and 20° lateral forces were extremely significant ($p < 0.001$).

Chapter 4, Section II

BEHAVIOR OF JAW MUSCLES OF TMD SUBJECTS

Two clinicians separately examined all the patients using the same standard Craniomandibular Index (see 3.II.4.b.) attached in Appendices Item #7. The two sets of examination results were generally very consistent. All the participating patients had Angle's Class I occlusion and were free from any medication which might have directly interfered with contraction of skeletal muscles.

All patients had difficulty producing bite forces in the required directions. Whenever a patient reported that he/she had minor pain, the force transducer was removed and the experiment was not resumed until the patient agreed; whenever a patient reported that there was moderate pain, the experiment was terminated. A large amount of data was discarded because some patients were not able to maintain tasks (for 4 seconds) which they successfully initiated. As a result, most patients only performed one task in each of the specified bite force directions. Therefore, the number of tasks performed by each patient was less than expected.

The limited number of patients was due to lack of suitable candidates who would conform with the selection criteria. EMG muscle patterns of the TMD subjects were not treated with statistics because (1) the sample size was not sufficiently large and (2) no assumption could be made that the patients' data would form a normal distribution.

4.II.1...CASE I

Case I was a Caucasian female high school student aged 18 years. Her chief complaints were chronic, and sometimes severe, pain in jaw muscles, mainly in the right masseter area, for about half a year. She had an inconsistent unilateral chewing habit (left side preferred) because of the pain.

4.II.1.a...Clinical examination

The following positive signs were found ($^+$:identified by one examiner; $^{++}$: identified by two).

1) Muscles tenderness:

- a) right masseter^{++} (both its superficial and deep portions);
- b) right medial pterygoid$^+$;
- c) right posterior digastric$^+$.

2) Joint dysfunction:

- a) 'S' shaped deviation (Right→Left)$^{++}$;
- b) reproducible opening click in the right joint$^+$;
- c) reproducible closing click in the left joint$^+$;
- d) painful right-side TMJ capsule^{++}.

4.II.1.b...EMG muscle patterns

Bite force tasks were performed on the ***right*** (affected) side of the jaw. MVBF on the right side was 280 *N* and its direction was -6°, -12° (F-B angle and L-R angle in Figure 8, *p*. 184). The magnitude of all the bite force tasks was 100 *N* (about 30% of the maximum bite force); the directions were vertical and 20° forward, backward and medial. The patient was not able to produce any lateral bite force.

Differences between the ratios of paired muscles compared to those of the corresponding ratios found in normal subjects were as follows:

1) increased ratios of the working temporalis over the working masseter for the 20° forward bite force (Figure 29B, *p*. 225): 1.57 (normal: 0.87±0.14) and for the 20° medial bite force (Figure 29D): 1.45 (normal: 1.04±0.21);

2) decreased ratio of the balancing temporalis over the balancing masseter for the 20° medial bite force (Figure 30D, *p*. 226): 0.63 (normal: 1.06±0.27);

3) increased ratio of the working temporalis over the balancing temporalis for the 20° medial bite force (Figure 31D, *p*. 227): 1.53 (normal: 1.00±0.25);

4) decreased ratios of the working masseter and the balancing masseter for the 20° backward bite force (Figure 32C, *p*. 228): 0.77 (normal: 1.21±0.17) and for the 20° medial bite force (Figure 32D, *p*. 228): 0.66 (normal: 0.97±0.09).

According to these ratios, the following muscles seem to be used less than those in the normal group:

1) the working (right) masseter (as compared to both the working temporalis and balancing masseter);

2) the balancing (left) temporalis (as compared to both the balancing masseter and the working temporalis).

4.II.2...CASE II

Case II was a Caucasian female cook assistant aged 37 years. Her chief complaints were constant dull pain in the left jaw muscles and jaw joint for about 2 years.

4.II.2.a...Clinical examination

The following positive signs were found ($^{+}$:identified by one examiner; $^{++}$: identified by two).

1) Muscles tenderness:

   a) left masseter^{++} (including superficial and deep portions);

   b) left posterior temporalis and temporalis insertion^{+};

   c) left lateral pterygoid^{++};

   d) left posterior digastric^{+}.

2) Joint dysfunction:

   painful left-side posterior TMJ capsule^{+}.

4.II.2.b...EMG muscle patterns

Bite force tasks were performed on the ***right*** (unaffected) side of the jaw. MVBF on the right side was 500 *N* and its direction was 2°, -13° (F-B angle and L-R angle in Figure 8). The magnitude of all the bite force tasks was 150 *N* and/or 300 *N* (about 30% to 60% of the maximum bite force); the directions were vertical and 20° forward, backward and medial. The patient was not able to produce any lateral bite force.

Apparently different ratios of paired muscles compared to those of the corresponding ratios found in normal subjects were as follows:

1) increased ratio of the working temporalis over the working masseter for the 20° medial bite force (Figure 33D, *p*. 229): 1.63 (normal: 1.04±0.21);

2) increased ratios of the balancing temporalis over the balancing masseter for the vertical bite force (Figure 34A, *p*. 230): 1.60 (normal: 1.04±0.26), for the 20° forward bite forces (Figure 34B, *p*. 230): 2.96 (normal: 0.65±0.20) and for the 20° backward bite forces (Figure 34C, *p*. 230): 2.36 (normal: 1.45±0.26);

3) increased ratios of the working over the balancing temporal muscles for the 20° backward bite force (Figure 35C, *p*. 231): 2.15 (normal: 1.52±0.38) and for the 20° medial bite forces Figure 35D): 1.45 (normal: 1.00±0.25);

4) decreased ratios of the working masseter over the balancing masseter for the 20° forward bite force (Figure 36B, *p*. 232): 0.82 (normal: 1.01±0.09) and for the 20° backward bite force (Figure 36C): 0.77 (normal: 1.21±0.17).

These ratios seemed to indicate that the following muscles were probably rather inactive compared to the corresponding normal ones:

1) the balancing (left) masseter (as compared to balancing temporalis);

2) the balancing (left) temporalis (as compared to working temporalis);

3) the working (right) masseter (as compared to balancing masseter).

4.II.3...CASE III

Case III was a Caucasian female clerk aged 38 years. Her chief complaints were migraine headache and severe jaw muscle pain for two and half years. She was undertaking social counselling for TMD and other issues.

4.II.3.a...Clinical examination

The following positive signs were found ($^{+}$:identified by one examiner; $^{++}$: identified by two).

(1) Muscles tenderness:

a) left and right anterior temporal muscles^{+}

b) left and right middle temporal muscles^{++}

c) left and right posterior temporalis muscles^{++}

d) all portions of left and right masseters^{++}

d) left and right medial pterygoid (intra- and extra-oral examinations)$^{++}$

e) left and right posterior digastric^{++}

f) left and right lateral pterygoid^{++}

One examiner noted, on his clinical examination sheet, that the patient indicated that bilateral superficial masseters were more tender than other muscles.

(2) Joint dysfunction:

painful left and right TMJ capsules^{++}.

4.II.3.b...EMG muscle patterns

Bite force tasks were performed on the ***left*** side of the jaw. The MVBF on the left side was 420 *N* and its direction was -10°, 3° (F-B angle and L-R angle in Figure 8). The magnitude of all the bite force tasks was 70 *N*, 100 *N* or 300 *N* (about 6% to 70% of the maximum bite force); the directions were vertical and 20° forward, backward, medially and laterally.

Apparently different ratios of paired muscles compared to those of the corresponding ratios found in normal subjects were as follows:

1) increased ratio of the working temporalis over the working masseter for the 20° forward bite force (Figure 37A, *p*. 233): 1.54 (normal: 0.87±0.14), for the vertical bite force (Figure 37B): 1.81 (normal: 1.12±0.23), for the 20° backward bite force (Figure 37C): 3.11 (normal: 1.90±0.38), and for the 20° medial bite force (Figure 37D): 1.47 (normal: 1.04±0.26); however, the same ratio for the 20° lateral bite force was reduced: 0.91 (normal: 2.34±1.29);

2) increased ratio of the balancing temporalis over the balancing masseter for the vertical bite force (Figure 38B, *p*. 234): 2.16 (normal: 1.04±0.26) and for the 20° backward bite force (Figure 38C): 3.33 (normal: 1.45±0.26); however, the same ratio for the 20° medial bite force was reduced (Figure 38D): 0.54 (normal: 1.06±0.27);

3) decreased ratio of the working temporalis over the balancing temporalis for the vertical bite force (Figure 39B, *p*. 235): 0.65 (normal: 1.27±0.45), the 20°

backward bite force (Figure 39C): 0.73 (normal: 1.52±0.38) and the 20° lateral bite force (Figure 39E): 0.52 (normal: 1.82±0.56);

4) decreased ratios of the working masseter over the balancing masseter for the 20° forward bite force (Figure 40A, *p*. 236): 0.51 (normal: 1.01±0.09), the 20° backward bite force (Figure 40C): 0.78 (normal: 1.21±0.17) and the 20° medial bite force (Figure 40D): 0.47 (normal: 0.97±0.47).

These many possibly abnormal ratios as compared to those of the normal group indicate that the following muscles were probably rather inactive:

1) the working (left) masseter (as compared to both the working temporalis and the balancing masseter); however, the working temporalis seemed to be inactive (as compared to working masseter for the 20° lateral bite force);

2) the balancing masseter (as compared to balancing temporalis); however, the balancing temporalis appeared to be rather inactive for the 20° medial bite force;

3) the working (left) temporalis (as compared to balancing temporalis).

4.II.4...CASE IV

Case IV was a Caucasian female clerk aged 32 years. Her chief complaints were earache and jaw muscle pain for two and half years. She also reported that her jaw muscles usually 'fatigued' when chewing food. She received an occlusal splint about one year earlier and it did little to relieve her symptoms.

4.II.4.a...Clinical examination

The following positive signs were found ($^{+}$:identified by one examiner; $^{++}$: identified by two).

(1) Muscles tenderness:

On the left side

a) anterior temporal muscles^{++}
b) posterior temporalis muscles^{+}
c) superficial masseters^{++}
d) lateral pterygoid^{++}

On the right side

a) medial pterygoid^{+}
b) posterior digastric^{++}
c) temporalis insertion^{+}
d) lateral pterygoid^{++}

(2) Joint dysfunction:

painful left TMJ capsule^{++}; painful lateral right TMJ capsule.

4.II.4.b...EMG muscle patterns

Bite force tasks were performed on the ***right*** side of the jaw. The MVBF on the right side was 290 *N* and its direction was 17° medially. The MVBF on the left side was 190 *N* and its direction was -11°, 27° (F-B angle and L-R angle in Figure 8). The magnitude of all the other bite force tasks was 150 *N* (about 50% of the maximum bite force); the directions were vertical and 20° forward and medial. The patient was not able to produce any lateral or posterior bite forces on the right side.

Apparently different ratios of paired muscles compared to those of the equivalent ratios found in normal subjects were as follows:

1) decreased ratio of the working temporalis over the working masseter for the 20° forward bite force (Figure 41A, *p*. 237): 0.32 (normal: 0.87±0.14).

2) the ratio of the balancing temporalis over the balancing masseter being decreased for the 20° forward bite force (Figure 42A,*p*.238): 0.13 (normal: 0.65±0.20) and increased for the 20° medial bite force (Figure 42C): 1.78 (normal: 1.06±0.27);

3) decreased ratio of the working over the balancing temporal muscles for the 20° medial bite force (Figure 43C, *p*. 239): 0.56 (1.00±0.25);

4) decreased ratio of the working over balancing masseters for the vertical bite force (Figure 44B, *p*. 240): 0.66 (1.03±0.21).

These ratios seem to suggest that the following muscles were rather inactive compared to those corresponding ratios of the normal group:

1) the working (right) temporalis (as compared to both the balancing temporalis and the working masseter);

2) the working masseter (as compared to the balancing masseter).

3) the balancing (left) temporalis for the 20° forward bite force and balancing masseter for the 20° backward bite force.

4.II.5...CASE V

Case V was a Caucasian male high school student aged 32 years. His chief complaints were headache and pain in jaw/facial muscles for about 1 year. His lower jaw was injured about one and a half year ago. He also reported clicking sound in the right joint.

4.II.5.a...Clinical examination

The following positive signs were found ($^{+}$:identified by one examiner; $^{++}$: identified by two).

(1) Muscles tenderness:

right deep masseter^{++}

(2) Joint dysfunction:

painful right TMJ capsules^{++}.

4.II.5.b...EMG muscle patterns

Bite force tasks were performed on the ***Right*** (affected) side of the jaw. His maximum bite force on the right side was 740 *N* (average: 600 *N* for about 6 seconds) with a direction of -7°, -8° (F-B angle and L-R angle in Figure 8). The magnitude of all the other bite force tasks was from 50 *N* to 200 *N* (about 7% to 27% of the maximum bite force); the directions were vertical and 20° forward, backward, medially and laterally. The patient remarkably produced 20° lateral bite forces at 150 *N* and 200 *N* with two separate trials.

The only apparently deviated ratio was that of working and balancing masseters for the 20° backward bite (Figure 48B, *p*. 244) being 0.51 (normal:1.21±0.17); this decreased ratio indicates that the working masseter was rather inactive. Most, if not all, other ratios were within the range of those of the normal group (Figures 45 to 48, *pp*. 241-244).

4.II.6...CASE VI

Case VI was a Caucasian female waitress aged 49 years. Her chief complaints were constant dull pain in the left jaw muscles and jaw joint for about 4 years.

4.II.6.a...Clinical examination

The following positive signs were found ($^{+}$:identified by one examiner; $^{++}$: identified by two).

Muscles tenderness:

a) left deep masseter^{++};

b) left superficial masseter^{++}

c) left medial pterygoid^{+}

d) left posterior digastric^{+}.

4.II.6.b...EMG muscle patterns

Bite force tasks were only performed on the ***left*** side of the jaw. The MVBF on the left (affected) side was 120 *N* and its direction was 10°, 19° (F-B angle and L-R angle in Figure 8, *p*. 184). The MVBF on the right (unaffected) side was 160

N and its direction was 2°, -16° (F-B angle and L-R angle in Figure 8). The magnitude of all the bite force tasks was 70 *N* (about 60% of the maximum bite force); the directions were vertical and 20° forward, backward.

Apparently different ratios of paired muscles compared to those of the equivalent ratios found in normal subjects were as follows:

(1) decreased ratio of the working temporalis over working masseter for the vertical bite force (Figure 49B, *p*. 245): 0.79 (normal: 1.12±0.23);

(2) increased ratio of balancing temporalis and balancing masseter for the 20° backward bite force (Figure 50C, *p*. 246): 2.58 (normal: 1.45±0.26);

(3) decreased ratio of working and balancing temporal muscles for the 20° backward bite force (Figure 51C, *p*. 247): 0.76 (normal: 1.52±0.38).

According to these ratios, the following muscles seem to be used less than those in the normal group:

1) the working (left) temporalis;

2) the balancing (right) masseter.

CHAPTER 5

DISCUSSION AND CONCLUSIONS

5.I...DISCUSSION

- 5.I.1...The bite force transducer...124
- 5.I.2...Direction of a mechanical force as a result of muscle contraction...127
  - .a...Direction as an independent motor control variable?...128
  - .b...Direction of a bite force...129
    - .(1)...Chewing force...129
    - .(2)...Submaximal isometric bite force...130
    - .(3)...Maximum voluntary bite force...131
- 5.I.3...Comparing with van Eijden *et al.* (1990)...133
- 5.I.4...Relation between bite force and surface EMG...136
- 5.I.5...Symmetry of muscle patterns...139
- 5.I.6...Co-activation of synergistic muscles...141
- 5.I.7...Recruitment patterns of jaw muscles...144
- 5.I.8...Muscle partitioning...147
- 5.I.9...Normal jaw muscle activity patterns...148
  - .a...Inter-muscle patterns...149
  - .b...Individual muscle patterns...149
- 5.I.10...Muscle activity patterns of TMD subjects...151
  - .a...Unilateral pain cases...151
    - .(1)...Case I...151
    - .(2)...Case II...153
    - .(3)...Case V...154
    - .(4)...Case VI...155
  - .b...Complex pain cases...155
    - .(1)...Case III...156
    - .(2)...Case IV...157
  - .c...Summary...158

5.II...CONCLUSIONS

Chapter 5, Section I

DISCUSSION

5.I.1...THE BITE FORCE TRANSDUCER

Force, like stress, is not a directly measurable quantity. The effect of a force, however, can be measured as strain or displacement. The determination of the direction and magnitude of a resultant force acting at a point in 3-dimensional space requires the measurement of strain in three directions on each of three perpendicular planes. The bite force transducer developed for the present study has the following advantages and disadvantages to fulfil the above requirements.

The force transducer was 2 *mm* thick and separated the incisors by 4 *mm* when placed unilaterally between the occluding first molars. The strain gauge rosettes used as sensors seemed to be sufficiently sensitive when installed onto the **H** shaped stainless steel (gauge 20) housing. This bite force transducer has the following advantages compared to the 3-element piezo-electric force transducer, being used by the Amsterdam group, which separates the upper and lower incisors by about 16 *mm* (van Eijden *et al.*, 1988*a*; van Eijden *et al.*, 1990).

(1) The H shaped housing allows the sensors to be removed from the part of the transducer between upper and lower teeth and to be installed on the two vertical plates of the **H**. It separated the maxilla and mandible to a minimal extent and hence stretched jaw closing muscles to roughly the amount by which they are stretched during chewing food. It also reduced the amount of passive tension generated by jaw closing muscles due to being stretched and therefore the muscle

tensions measured with it are probably closer to the active tensions exerted for the required tasks.

(2) Its thickness and small size are less likely to induce fatigue in jaw muscles when subjects perform bite force tasks. Jaw muscles seem to be fatigable at both maximal and submaximal contraction levels (Christensen and Mohamed, 1984; Kroon *et al.*, 1986; Mao *et al.*, 1992*a*). Van Eijden *et al.* (1990) discussed possible fatigue-inducing effects of using their force transducer. Some normal subjects in the present study also reported feelings of 'fatigue' or 'tiredness' near the end of a session during which bite force tasks were produced. However physiological fatigue did not seem to have developed. The perception of 'fatigue' appeared to be related to 'central (psychological) fatigue' rather than the actual failure in the signal transmission of action potentials or contraction of muscle fibers (Mao *et al.*, 1992*a*). In fact, the subjects indicated that the feeling of fatigue was not significant and did not prevent them from continuing the experiments.

(3) Its thickness can be increased by increments up to about 20 *mm*. Thus, it can be used to study the length-tension relationship of jaw closing muscles. For example, it is interesting to consider whether the length-tension relations of jaw muscles for producing bite forces in various directions would be different.

(4) It is placed between one pair of the occluding teeth. The Amsterdam force transducer covers the whole upper and lower dentition. In the present study, the periodontal perception of a bite force was from those periodontal receptors

located around only the pair of occluding teeth between which the transducer was placed. Therefore, the afferent information seemed more precise. In addition, it can be, and has been, used to study incisal bite forces (Osborn and Mao, 1992). The Amsterdam transducer, in the present shape, does not seem to be capable of recording incisal bite forces.

The force transducer used in the present study, on the other hand, has the following shortcomings.

(1) It has so far been home-made. As a result, the construction and calibration have required a considerable amount of time which might have been used for collecting data. This might be overcome by transferring the technology to a manufacturer (and is being pursued).

(2) The housing is made of irregular material. Calibration has been empirical and different from one transducer to another. The soldering points of the **H** shaped stainless steel housing appear to be more susceptible to force than the rest of the housing and have failed. This has resulted in building several force transducers and added additional cost to this seemingly more cost-efficient transducer than the Amsterdam one. This problem might be solved by casting the housing.

(3) An ideal 3-D force transducer should be equally sensitive to, and operate independently of, the forces in the three planes. In general, the force transducers used for the present study seem to be more sensitive to forces projected onto the sagittal plane than those projected onto the frontal plane. Therefore, 'cross-talk' between channels seems to be responsible for the fact that one plane picks up a

portion of the information intended for a different plane. This drawback, however, was turned into an advantage through an empirical relationship which calibrates the out-of-plane information into a repeatable measurement of force acting out of the two parallel planes. Therefore, it may be true that the irregularity of the housing material has provided the opportunity for the transducers to detect differences in the directions of bite forces in the frontal plane (see also Appendices Item #4).

5.I.2...DIRECTION OF A RESULTANT FORCE OF SYNERGISTIC MUSCLES

The direction of a mechanical force measured as the resultant muscle force output has been less extensively studied than its magnitude. The results of the present study seem to suggest that control of the direction of such a force be as important as its magnitude by the central nervous system. If this is true, the following peculiarities of the human jaw motor system must be borne in mind before any attempt to apply the conclusion to other locomotor systems.

(1) The jaw closing muscles can produce overwhelmingly more force than their antagonists, the jaw opening muscles (*e.g.* Williams and Warwick, 1980; Sicher and DuBrul, 1975). Thus, when jaw closing muscles are activated to produce a bite force, they probably have to allocate extra muscle elements to keep an equilibrium state without relying upon their antagonists to counteract some of the unwanted force components.

(2) All the jaw closing muscles are multi-pennate and have broad attachment areas in the skull (*e.g.* Williams and Warwick, 1980; Sicher and DuBrul, 1975). This seems to form the anatomical basis for muscle partitioning discussed below (5.I.8.).

(3) Golgi tendon organs are possibly absent from human jaw closing muscles (Bratzlavsky, 1975) whose function might have been partially replaced by periodontal mechano-receptors (Lavigne *et al.*, 1983; Olsson *et al.*, 1988). Periodontal mechano-receptors are closer to the load and detect the direction of a bite force (Hannam, 1976) but are separated from muscles as compared to a Golgi receptor which is connected to about a dozen muscle fibers (Dowben, 1980; Desmedt, 1980).

(4) The size of type IIB (fast-twitch and fatigue-susceptible) muscle fibers is smaller than type I (slow-twitch) fibers in human jaw closing muscles and, in addition, type IIA (fast twitch and fatigue-resistant) fibers are almost absent (Eriksson and Thornell, 1983; Herring, 1991; Mao, Stein and Osborn, 1992*c*).

(5) Fibers of the same type normally cluster (Herring, 1991; Stalberg *et al.*, 1986; Stalberg and Eriksson, 1987). In other words, the motor unit territory is very restricted (Stalberg *et al.*, 1986; Stalberg and Eriksson, 1987). Quantitatively, Herring *et al.* (1989) showed that muscle fibers of a single motor unit in pigs occupied as little as 5% of the cross-sectional area.

(6) The left and right sides of the human mandible are fused and have separated left and right temporomandibular joints which must function in unison.

This anatomical peculiarity forces the muscles on the left and right sides of the jaw to be coordinated.

5.I.2.a...Force direction as a motor control variable

In the present study the direction of a bite force was found to be correlated with fairly consistent muscle patterns. Van Eijden *et al.* (1990) had a similar conclusion. Despite the above peculiarities in human jaw muscles, the existence of some sort of direction-specific mechanisms controlling muscle tensions agrees with several observations of human and primate limb muscles. Evarts (1981) and Evarts *et al.* (1983) showed that neurons of the motor cortex discharge selectively depending on the direction and magnitude of forces used in forthcoming movements. Rosenbaum (1980) indicated that the direction and magnitude of a force were separable components of motor control (see also Soechting and Terzuolo, 1990). Georgopoulos *et al.* (1982 and 1983) proposed that the directions of some arm movements were probably encoded in shoulder-related motor cortex neurons; in other words, different cells may be responsible for initiating different directions of movement. Georgopoulos *et al.* (1986 and 1988) provided experimental evidence for the above postulates: the discharge of certain motor cortex cells varied with the patterns of muscle activity and directions of output forces required to produce movements (see also Kalaska *et al.*, 1989). Thus, a tentative conclusion might be reached from the above studies in jaw and limb muscles: in allocating tensions among synergistic muscles the direction of a force might be as importantly weighted as its magnitude by the central nervous system.

5.I.2.b...Direction of a bite force

Bite forces can be measured at submaximal and maximal levels. Submaximal bite forces, in a broader sense, include (dynamic) chewing force and static submaximal bite forces. Maximal voluntary bite forces are seldom used in chewing food but may reveal some interesting features of jaw muscles.

5.I.2.b.(1)...Chewing force

The direction of a chewing force changes momentarily during the power stroke phase of mastication because the relations between opposing occlusal surfaces change as the lower teeth sweep past the upper teeth (*e.g.* Mills, 1973; Hiiemae and Kay, 1973). The direction is also probably changed by a subject in response to the mechanical properties of the food (*e.g.* Bishop *et al.*, 1990; Diaz-Tay *et al.*, 1991). It has been argued that the curves of Monson and of Spee, to which the occlusal surfaces of molar teeth are aligned, are important in processing food because they also affect the crush/shear ratio of the forces applied to the food in between them (Davis, 1964; Greaves, 1978; Osborn, 1986; Osborn, 1992).

Chewing forces have been studied (Anderson, 1953, 1956*a*, 1956*b*; De Boever *et al.*, 1978; Graf *et al.*, 1974; Laurell and Lundgren, 1984; Lundgren and Laurell, 1984; Neill *et al.*, 1989). Among these only Graf *et al.* (1974) were able to measure the chewing force in three dimensions but there has not been any subsequent study using the same device. The techniques used in building the force transducer in the present study may be used to construct a chewing force transducer. For example, 3-element strain gauge rosettes can be incorporated into a removable denture. Such a chewing force transducer would be useful in studying dynamic bite forces generated in mastication in humans or in animal jaw muscles under electrical stimulation.

5.I.2.b.(2)...Submaximal isometric bite forces

Submaximal isometric bite forces in various directions were used as standard tasks in the present study: each of the five directions (20° forward, 20° backward, vertical, 20° medial and 20° lateral) was separated by 90° in the horizontal plane. The muscle patterns expressed as ratios between pairs were significantly different in most cases (*p* values less than 0.001). There still appears to be room to test muscle patterns by using bite forces with directions closer to each other (*e.g.* 30°, 20°, 10° forward, the vertical, and 10°, 20°, 30° backward). Blanksma and van Eijden (1990) showed some characteristic patterns of three parts of temporalis by using forces which were 20° from the vertical and 45° from each other in the horizontal plane.

It might be argued that the difficulty initially encountered by normal subjects to find the required direction of bite forces does not seem to support the conclusion that the central nervous system initially controls the direction of a bite force. This may be accounted for by the fact that people are not used to visualizing the performance of their jaw muscles as they might, for example, do with their limb muscles as in sports. Therefore, provision of a visual feedback of bite forces might have initially complicated, rather than improved, the perception of a bite force direction which is normally perceived via those force-detecting proprioceptors such as periodontal mechano-receptors (or Golgi tendon organs in limb muscles). Two such examples of an added input confusing perception are using dental floss while watching in a mirror and using a joy stick for a computer game.

5.I.2.b.(3)...Maximum voluntary bite force (MVBF)

The angles chosen by normal subjects to produce MVBFs were not vertical but a small angle (less than 15°) to the medial with a slight antero-posterior deviation from the vertical (experimental observation). Van Eijden *et al.* (1990) agreed with the medial component but added that the direction for a MVBF was usually posterior. The discrepancy might be related to different amount of jaw separation which is discussed below in (5.I.3). In the present study, the directions chosen by TMD subjects to produce MVBFs were recorded and discussed below in 5.I.8.

Measured with a uni-directional force transducer, the maximum bite force on the first molar (M1) is greater than the maximum bite force on M2 (reviewed by Carlsson, 1974; Worner and Anderson, 1944). This is surprising because M2 is nearer the fulcrum, the jaw joint(s). A three dimensional computer jaw model (Baragar and Osborn, 1987) proved, somewhat obviously, that the maximum bite force on M2 was theoretically larger than that on M1. But if work done crushing food, rather than the force applied to it, was taken as the criterion of biomechanical efficiency then M1 was more efficient than M2. In fact, Mansour and Reynik (1975*a* and 1975*b*) found, in one subject, that MVBF produced on M2 was 10% greater than that on M1. It would be interesting to test whether the direction of MVBFs produced on M1 and M2 are different.

The maximum bite force is increased if visual feedback is provided (Dahlstrom *et al.* 1988). These authors concluded that the weaker performance of subjects lacking a visual feedback was due to reluctance to bite harder. The result could also be explained by the inability of subjects, without feedback, to find the direction in which the maximum bite force could be produced.

Lund and Lamarre (1973) showed that when periodontal afferents were anaesthetized the maximum bite force on a premolar, measured by a unidirectional force transducer, decreased by 40%. They suggested the existence of a positive feedback from periodontal afferents, possibly through a different group of interneurons which increased the maximum bite force (Lavigne *et al.*, 1987; Olsson *et al.*, 1988). Conflicting results were reported by van Steenberghe and de Vries (1978*b*), Orchardson and MacFarlane (1980), and recently by Teenier *et al.*, (1991). The different results may be due to the fact that, in the absence of an afferent input, subjects could not find the direction which maximizes the bite force (Osborn *et al.*, 1986). This hypothesis could be tested with the transducer described in the present study.

The maximum static bite force on the central incisors is theoretically achieved by a force backward from the vertical (Baragar and Osborn, 1987; Koolstra *et al.*, 1988). If, however, cutting efficiency is the criterion used for choosing the direction for incising then the most efficient direction is theoretically forward from the vertical (Osborn *et al.*, 1986). Hylander (1978) found that a static bite force produced on lower central incisors was anteriorly oriented. Osborn and Mao (1992) showed that the initial direction chosen by normal subjects to generate MVBFs on lower central incisors was in the range of 10° to 14° anteriorly from the vertical.

5.I.3...COMPARING WITH van Eijden *et al.* (1990)

Van Eijden *et al.* (1990)'s data, which are the only comparable data obtained under similar conditions, were adapted into the same format as the data obtained from the normal subjects in the present study (Figure 53, *p*. 249). The general similarities were considerable. In every case the most active muscle and the least active muscle are either the same or indistinguishable. In three cases, all for bites parallel to the sagittal plane (including the vertical), the second most active muscle was either the same or indistinguishable (roughly equal activity in several muscles) (Figure 53A & A', B & B', C & C', *p*. 249). This is the first time that EMG data of jaw muscles have been truly comparable and may explain why the results are so alike. The fundamental reason seems to be that the magnitude and direction of bite forces were known and used as standard tasks in both studies.

There are, however, some important differences which should not be ignored. (1) For a forward bite force (Figure 53A & A', *p*. 249), the working and balancing masseters were proportionally more activated than the corresponding temporal muscles in the present study; the activity of the same four muscles was indistinguishable in the van Eijden *et al.* (1990) data. (2) For vertical and medial bite forces (Figure 53C & C', D & D'), the four muscles contracted roughly to the same degree in the present study; while in van Eijden *et al.* (1990), the activity of the four muscles was more separated. (3) No subject could produce a stable lateral bite force beyond 150 *N* in the present study while in van Eijden *et al.* (1990) lateral bite forces were produced up to 450 *N* (Figure 53E & E'). (4) More muscle tension was used to produce the forward, backward and vertical bite forces in the present study. (5) Regression lines representing percentage EMG activity of all the muscles passed closer to the origin of the coordinates in the present study.

Some of the above differences might be attributed to jaw separation. When the upper and lower jaws are widely separated, less muscle effort seems to be required for the same bite force (*e.g.* Herring, 1991; Mackenna and Turker, 1983; Manns *et al.*, 1979) although the length-tension relation in jaw muscles remains unsettled. If this is true, then muscle tensions measured with the thin force transducer in the present study should be more, which is the case, than those measured with the thicker Amsterdam transducer. A larger jaw separation may also explain the posterior angle found as a component of the direction of MVBF in van Eijden *et al.* (1990): the MVBF was somewhat posteriorly directed.

Another explanation for the apparently larger muscle tensions used for the above-mentioned bite force directions in the present study may be related to the way in which EMG_{max} was calculated. The average of the 200 largest EMG data point was regarded as EMG_{max} in the present study, while in van Eijden *et al.* (1990) a single largest EMG data point was used. Therefore, it is very likely that the greater EMG_{max} used by van Eijden *et al.* (1990) resulted in lower percentage EMG activity values.

An anatomical difference is noted in using different standards in measuring the direction of a bite force. Van Eijden *et al.* (1990) used the Frankfurt plane, which passes through the two orbital points and poria (Sicher and DuBrul, 1975: orbitale being the lowest point at the infraorbital rim and porion being the most lateral point on the roof of the external auditory meatus). In the present study, the maxillary occlusal plane was used.

The EMG regression lines in van Eijden *et al.* (1990) were generally more distant from the origin of the coordinate system than those in the present study. This means that the Y intercept values (c), in the form of $Y = mX + c$, were greater in their case than in the present study ($c = 3.72 \pm 4.11$ as mean±S.D.). The c values have at least two attractive features: (1) when c values are close to the origin (zero), activity ratios of a muscle pair are constant as in the present study. (2) Since the only apparent difference in methodology between the present study and van Eijden *et al.* (1990) is jaw separation, the *c* value might be positively correlated with jaw separation.

5.I.4...RELATION BETWEEN FORCE AND SURFACE EMG

Approximately linear relations were found between incremental bite forces of the five studied directions and the majority of the corresponding EMG activity of the jaw muscles for producing them; EMG activity for vertical and medial bite forces showed better linear correlations (and smaller variation) than bite forces in the other three directions (Table 6 - *p.* 168). The averaged correlation coefficients (*r* values) for the five force directions were greater than 0.80 indicting positive linear correlations. The *r* values for any particular task of all individuals showed, of course, greater variations: 0.87±0.17 (mean±S.D.) with a range of 0.28 to 0.99.

The linearity between the integrated EMGs of the four muscles and the graded bite forces in the five directions found in the present study is original. Van Eijden *et al.* (1990), the only other study in which the relation was examined in the same bite force directions, did not provide *r* values, nor did they comment on linearity. On the other hand, the EMG activity of jaw muscles has been correlated with graded bite forces measured with uni-directional force transducers. Yemm (1977*a*) showed a fairly linear correlation between masseter surface EMG and bite forces. Kawazoe *et al.* (1979) found extremely good correlation coefficients (from 0.96 to 0.99) but these values were calculated from the most linear parts of both the

EMG and force waveforms over those recorded during 15 minute gradually increasing isometric clenching. Moller (1975) found 0.63 to 0.70 as the range of *r* values. Bakke *et al.* (1989) showed that the linear correlation between unilateral bite forces and the averaged bilateral masseter and temporalis EMG activity was 0.71 to 0.94. Linear correlation between EMG activity of the above muscles and bite forces measured bilaterally was poor.

The relation between graded isometric force generated by a muscle and its integrated surface EMG activity has been found to be approximately linear since the 1950's (Lippold, 1952; Inman *et al.*, 1952). Milner-Brown and Stein (1975) observed that the measured surface EMG contributed by a single motor unit increased as the square root of the threshold force at which the unit was recruited; but the surface EMG contributed by compound action potentials in the muscle, which may sum non-linearly at moderate to high force levels, would still change in a linear fashion with the force. The present study contributes to this seemingly-solved problem in that linearity may also exist between the integrated surface EMG and mechanical forces in several directions although the relations are apparently closer to linear for some directions than others.

The bite forces (up to 300 *N*) used in the present study were probably not the maximum voluntary forces, although some in certain directions for certain individuals may have reached the maximum. Judging from the linearity observed between the graded forces and EMGs in all the five directions (Figures 15 to 21, *pp*. 198-210), deviation at high force levels is not necessarily greater than at low force levels. This can be attributed to the following factors. (1) The larger forces (up to 300 *N*) used in the present study were probably only moderate compared to the maximum voluntary bite forces which could have been produced by most subjects. Hence, the range was probably still within that in which linearity has usually been observed. (2) Milner-Brown, Stein and Yemm (1973*a* and 1973*b*) showed that gradation of muscle forces was due to the recruitment of new motor units at low force levels and an increase in firing rate and greater synchronization at high force levels (see also De Luca, 1979). It might be that the weaker forces, largely contributed by tensions due to recruiting new motor units, were more linear with the EMG output. (3) The direction of bite forces was a task which was sufficiently specific to have resulted in the constantly proportional contribution of the masseter and temporalis.

Pruim *et al.* (1978) showed that the EMG activities of superficial masseter and anterior temporal muscles were not linearly correlated with bilateral isometric bite forces, especially at high force levels. Their results seemed to be in agreement with those of Bakke *et al.* (1989) in that bilateral bite forces correlated poorly with EMG activity. Pruim *et al.*'s (1978) results, on the other hand, seem to partially agree with those of Hagberg *et al.* (1985) and Haraldson *et al.* (1985) in that masseter EMG had poorer correlation with bite forces than temporalis. This is in partial agreement with the present study in that all the four *r* values less than 0.50 were correlated with masseter muscles (Figures 17 to 19, *pp*. 202-206): three for the balancing masseter and one for the working.

It has been shown that a linear relation exists between the force produced by a muscle weakened due to disease and its EMG activity (Leman, 1959*a* and 1959*b*). It is of interest to see if such linearity is preserved in the painful jaw muscles of TMD patients, some of which might have been injured. Unfortunately, this was not tested in the present study because all TMD subjects were only able to produce one magnitude of bite force for each of the particular bite force direction. It may form a testable hypothesis for TMD jaw muscles if TMD patients are only requested to produce incremental bite forces which are within the range of only small fractions of the MVBF (*e.g.* from 2 to 20% of MVBF).

5.I.5...SYMMETRY OF MUSCLE PATTERNS

The bilateral muscle patterns obtained for tasks on the left side of the jaw showed a mirror image for equivalent tasks on the right side. This seemingly self-evident result has surprisingly never been reported. Forward and backward bite forces, which are projected in the sagittal plane, and vertical forces showed better similarities than those projected in the frontal plane (lateral and medial forces). This may be attributed, for one thing, to the bite force transducers being more sensitive to forces in the sagittal plane than to those in the frontal plane. Medial forces were produced by similar EMG activity in the bilateral masseter and temporal muscles.

Lateral bite forces have been the most difficult to produce. None of the normal subjects managed to produce any lateral bite force above 150 *N* and most of them were not able to produce any lateral bite force. Although three subjects did manage to produce lateral bite forces up to 150 *N*, they had great difficulty producing and maintaining them. This was not true with van Eijden *et al.* (1990) in which lateral bite forces were produced up to 450 *N*. The difference between the two sets of results may be attributed to different amounts of jaw separation and hence the position of the condyles in their (temporomandibular) joints. In van Eijden *et al.* (1990) the jaws were separated by about 16 *mm*. As a result both the working and balancing side condyles were forward on to their articular eminences and could be allowed to be pushed in the lateral and medial directions. In the present study the jaws were separated by 4 *mm*. The working and balancing side condyles were largely constrained within the fossae and could not be pushed in the lateral or medial directions.

Naeije *et al.* (1989) showed that the activity of bilateral masseter and temporal muscles were asymmetrical at low levels of inter-cuspal clenching (10% of the maximum masseter EMG activity); when muscle tensions increased, there was less asymmetry. These results are not surprising because there is (1) possibly bilateral asymmetry in equivalent jaw muscles and (2) a lack of standardized bilateral electrode positions. From the perspective of bilateral bite forces, Pruim (1979) showed that a bite force was more evenly distributed bilaterally as the magnitude of bite forces increases. Nonetheless, both Naeije *et al.*'s and Pruim's results seem to be consistent with the discrepancy in the left and right muscle patterns in the present study.

The left and right similarities in muscle patterns are also useful to further validate the bite force transducer used in the present study. It seems very unlikely that the left and right similarities are due to coincidence. The mirror image of the left and right muscle patterns are also useful for confirming the accuracy of EMG recordings.

5.I.6...CO-ACTIVATION PATTERNS OF SYNERGISTIC MUSCLES

As might have been expected, a task has been shown to determine the relative contribution of a group of synergistic muscles to a given mechanical force they produce (Buchanan *et al.*, 1989; Osborn and Baragar, 1985; Flanders and Soechting, 1990; Kalaska *et al.*, 1989; Rosenbaum, 1990; van Eijden, 1990). However, tasks used in different studies are often different. In the present study, it is clearly indicated that the direction of the bite force, rather than its magnitude, induced the fairly constant ratios of tensions among jaw closing muscles (as a synergistic group). As the bite force directions were fixed as five distinctive tasks, most activation ratios of paired muscles were roughly constant, regardless of the magnitude of bite forces, and distinctive from each other. These results agree with the conclusion from van Eijden *et al.* (1990): patterns of muscle activity are specific to the direction of the bite force.

Certain patterns of synergistic muscle co-activation also seem to exist in the status of muscle fatigue. Hellsing and Lindstrom (1983) showed that the activity of the masseter was reduced and that of temporalis increased as subjects sustained their incisal bite forces until fatigue. Osborn and Mao (1992) found that the anteriorly oriented incisal bite force (possibly resulting from the greater activity in masseters) became more vertical during the course of sustained muscle contractions. They further argued that the switch in muscle activity observed by Hellsing and Lindstrom (1983) was very likely responsible for the change in the bite force direction. Later in an abstract submitted to the 1992 Society for Neuroscience convention, Mao, Stein and Osborn (1992*c*) confirmed that the anterior temporalis either maintained or increased its activity while superficial masseter decreased its tension during the same sustained tasks. From the above results, it seems possible that the drop in the activity of a fatiguing muscle may be compensated for by its synergistic partner(s).

Motor-unit and single-fiber recordings appear to indicate that muscle tensions are distributed in certain portions of jaw muscles in a fashion which is determined by tasks. When a uni-directional force transducer was oriented in two directions between the upper and lower incisors, twitch tension generated by some motor units in human masseter was significantly different (McMillan *et al.*, 1990). Inter-cuspal clenching and retrusion of the mandible also revealed different activity patterns in a sample of motor units in masseter and temporal muscles (Eriksson *et al.*, 1984).

Naeije *et al*. (1989) and Hagberg *et al*. (1985) both found that the masseter was more active than temporalis at relatively high isometric contraction levels. The present study suggests that their results would have been true only when the directions of the bite forces used in their studies were in the range from vertical to backward in the sagittal plane: the ratios of temporalis over masseter (for both the working and balancing sides) are in the range of about 1.04 to 1.90. The tasks used in Naeije *et al*. (1989) were inter-cuspal clenching which may be equivalent to somewhat backward bites in the present study, while those used by Hagberg *et al*. (1985) on a uni-directional force transducer were not possible to assess. In addition, both the results from Naeije *et al*. (1989) and Hagberg *et al*. (1985) seem to suggest that the ratios of temporalis over masseter would change with the magnitude of bite forces. This apparently conflicts with the results of the present study in which a muscle pattern was found to be specific to the direction of a bite force rather than its magnitude.

Beyond the scope of jaw muscles, it has long been recognized that the number of muscles acting across a joint exceeds the number of degrees of freedom available to the joint (*e.g.* Rosenbaum, 1990). Numerous attempts have been made to solve this degree-of-freedom problem which is fundamental in the control of movements. Some examples are as follows. Tax *et al*. (1989, 1990*a*, 1990*b*) consistently showed that the firing frequency of motor units in several elbow flexor muscles depended upon the direction of movement compared to static tasks: the firing frequency is higher in flexion and lower in extension than during isometric contractions. Buchanan *et al.* (1986) showed that elbow muscles during isometric contractions increased their tensions in a linear manner with increasing joint torque and their activity patterns varied with torque directions. Kalaska *et al.* (1989) argued that the direction of a force seemed to have considerable representation in motor cortex cells and might be preferably used to allocate tensions among muscles across joints with multiple degrees of freedom.

5.I.7...RECRUITMENT PATTERNS OF JAW MUSCLES

The recruitment of motor units in each muscle of a synergistic group affects the activity patterns measured with surface EMG. For example, constant ratios of two muscles which contain roughly equal amount of slow-twitch and fast-twitch fibers (*e.g.* human masseter and temporalis) can be anticipated as long as motoneurons in the two muscles are recruited in a sequence from the slow to the fast (and consequently the muscle fibers they innervate). The orderly recruitment pattern has been known as the 'size principle' (Henneman, 1957; Henneman *et al.*, 1965) and is true under many conditions of tasks (Desmedt, 1980). The 'size principle' has also been proven to hold in jaw muscles with motor-unit studies (Desmedt and Goudaux, 1979; Goldberg and Derfler, 1977; Yemm, 1977*a*).

There have been reports, however, indicating that the classic recruitment order may alter under certain conditions such as when a muscle functions among its synergistic partners (Desmedt and Godaux, 1981; Person, 1974; Ter Haar Romeny *et al.*, 1982; Thomas, Schmidt and Hambrecht, 1978). Synergistic muscles tend to share a load between them (Dul *et al.*, 1984*a* and 1984*b*). In fact, a change in the recruitment order is probably not universal and it was not observed in the 144 motor units of human first dorsal interosseous muscle during contractions to three directions studied by Thomas, Ross and Stein (1987). Calancie and Bawa (1990), in a recent review, concluded that the stereotyped recruitment order of small-before-large motor units is strongly supported for muscle contraction and deviations from this pattern during voluntary contractions, although demonstrated on occasion, are not easily reproduced.

Results from the present study seem to be supported by those studies which found that there was the orderly recruitment of jaw closing muscles. The orderly recruitment order of small before large motoneurons would allow for smooth increments of muscle tension at any level of contraction (Henneman and Olson, 1965; Harrison, 1983). The smoothed gradation of muscle force might be the foundation for the linear relations between the activity of surface EMG and bite forces in the present study. It might be further argued that such an orderly recruitment pattern also exists for forces in various directions. However, such immediate linkage may be unsafe considering the fact that surface EMG may still be roughly linear with the mechanical force while the actual muscle tension of a single motor unit increased as the square root of its threshold force (Stein and Milner-

Brown, 1975). In addition, human jaw muscles may be one of the exceptions to the 'size principle'. As stated before, the diameter of jaw closing muscle type IIB fibers (conventionally called 'large' fibers in limb muscles) is smaller than that of type I ('small fibers in limb muscles) fibers (Eriksson and Thornell, 1983; Herring, 1991; Mao *et al.*, 1992*b*; Ringvist, 1973*b*; Westbury and Shaughnessy, 1987). If these type II fibers would produce less twitch and tetanic tensions than type I fibers, their later recruitment might lead to less force output at moderate or high force levels. As a result, the orderly recruitment order would be distorted. However, there might exist some sort of mechanisms which would compensate for the decreased force against certain expectation: for instance, by recruiting a synergistic partner(s). These thoughts may lead to some testable hypotheses for studying the recruitment patterns in human jaw muscles. For example, one of the future extensions of the current study may focus on a question such as whether the recruitment order is distorted in motor units of several jaw muscles when performing different spatial tasks.

5.I.8...MUSCLE PARTITIONING

It is claimed that our knowledge of naming skeletal muscles originated from 16th century anatomical studies, *e.g.* by Da Vinci, and as a result the division of some muscles may not reflect their actual function. This statement may well be exemplified by jaw closing muscles most of which have broad attachment areas and all are multi-pinnate. For example, the upper and lower heads of lateral pterygoid function differently (Carlsoo, 1956; Grant, 1973; Widmalm *et al.*, 1987); masseter is usually divided into superficial and deep portions; temporalis is often described as having anterior, middle and posterior parts. The concept of muscle partitioning reflects synergism of various elements within one muscle or more possibly among several muscles.

Jaw muscles of the human and pig have been shown to have the potential of being compartmentalized (Herring *et al.*, 1979; Osborn and Baragar, 1985): by dividing muscles into independently controlled, spatially discrete volumes. Recent evidence on partitioning has focused on the human masseter (McMillan *et al.*, 1990; Tonndorf *et al.*, 1989; van Eijden and Raadsheer, 1992).

Muscle partitioning was thought to be related to (1) multi-pennation which serves to enable a muscle to produce more force with its volume in a limited space (English and Letbetter, 1982*a*; Gans and Gaunt, 1992; Herring, 1980; Osborn and Baragar, 1985; Weijs and Dantuma, 1981) and (2) rather independent control of various partitions (English, 1984; English and Weeks, 1984; Herring *et al.*, 1979 and 1989; Luschei and Goldberg, 1981). These two points are inter-correlated: independent control depends upon existing histological subdivisions.

The present study used surface EMG to measure the overall activity of jaw muscles and did not provide any direct evidence for muscle partitioning. However, a statement that jaw muscles are somehow partitioned would support the results obtained from normal subjects in the present study. The constant ratios of paired jaw muscles may well be accounted for by the relative contribution to tension of compartments in masseter and temporal muscles which are co-activated. For example, a fixed ratio (less than 1.00) of working temporalis over masseter might have been the result of 1) the more tension generated in an equal number of compartments in masseter than in temporalis and/or 2) more compartments involved in masseter than in temporalis. On the other hand, the present study can be logically expanded to ask a question about muscle partitioning: the specificity of tasks with the bite force transducer and intramuscular EMG would be useful in studying muscle partitioning in human subjects.

5.I.9...NORMAL JAW MUSCLE ACTIVITY PATTERNS

Some characteristic jaw muscle patterns were found in the normal subjects. Other than the mirror image muscle patterns for the left and right equivalent tasks, muscle patterns were generally found to be dependent upon the direction of bite force.

5.I.9.a...Inter-muscle patterns

Relative contribution, to a given bite force, of tensions among the four studied jaw muscles seems to be accounted for by their mechanical advantages being that superficial masseter is anteriorly oriented and anterior temporalis is somewhat vertically oriented. With this in mind, muscle patterns for the force directions in the sagittal plane (Figure 23A,C, *p*. 214) become self-explanatory. Forward bite force of 20° was associated with greater activity in masseter because the direction of bite force was parallel to the line of its resultant tensions; by the same token, a 20° backward bite force would be against the line of action of the masseter and closer to those of the middle and posterior temporal muscles. Vertical and 20° medial bite forces are probably aligned to the long axis of a lower molar and may involve the most efficient way of using jaw muscles as predicted by a computer model (Baragar and Osborn, 1987). In fact, the overall muscle activity for 20° medial bite forces (Figure 23D, *p*. 214) was less than that for other directions. Lateral bite forces of 20° were associated with more activity in working temporalis and masseter; this seems to be in partial agreement with the muscle activity for exerting lateral jaw movements (Herring, 1976; Vitti, 1971; Vitti and Basmajian, 1977).

5.I.8.b...Individual muscle patterns

The working temporalis was slightly more active for vertical bite forces than for 20° backward bite forces in the sagittal plane (Figure 24A, *p*. 216); it was most active for 20° lateral forces in the frontal plane (Figure 25A, *p*. 218). Probably, the middle and posterior temporalis (not measured in the present study) were activated to assist with the backward forces. The working temporalis was probably assisted by deep masseter to produce lateral forces.

The working masseter was found to be the most active muscle for 20° forward bite forces in the sagittal plane (Figure 24C) and for 20° lateral bite forces above 100 *N* in the frontal plane (Figure 25C). As described above, the great activity of masseter for forward bite forces can be attributed to its resultant line of action being somewhat anterior. Its dramatically increased activity for graded lateral bite forces was remarkable and may be accounted for by a demand at the high force level (above 100 *N*) because the activity of working temporalis was not sufficient.

The patterns for balancing temporalis and balancing masseter were distinguishable for force directions in the sagittal plane (Figure 24B,D) and were not distinguishable for those in the frontal plane (Figure 25B,D). Intuitively, a changing force direction in the frontal plane would reveal more differences in the activity of bilateral muscles. The patterns of balancing muscles in the frontal plane are difficult to explain. In the sagittal plane, balancing temporalis (Figure 24B) followed the patterns of working temporalis and may be explained the same way; the balancing masseter (Figure 24B), however, showed somewhat different patterns from those of the working masseter. The slightly greater activity it had for vertical bite forces (than for the 20° forward bite forces) might be related to balancing the overwhelming activity of the working masseter for the 20° forward bite forces.

5.I.10...MUSCLE ACTIVITY PATTERNS OF TMD SUBJECTS

The clinical findings separately reported by two examiners were fairly consistent. This might be attributed to the reproducibility of the Craniomandibular Index which was found to have good inter-examiner correlations when it is used to identify muscle tenderness and joint dysfunction (Friction and Schiffman, 1986 and

1987). Muscle patterns identified by EMG are compared to the corresponding patterns in the normal group used as the control and to the tender muscles identified clinically. The following analysis is based upon the assumption that an injured muscle (or muscle elements), which may be subjectively painful and tender to palpation, would less likely be recruited than a healthy muscle (or muscle elements) since a different strategy of allocating tensions would achieve a required bite force task.

5.I.10.a...Unilateral pain cases

Case I, II, V, and VI were similar in that muscular tenderness was clinically identified in unilateral muscles.

5.I.10.a.(1)...Case I

The tender muscles identified were all on the ***right*** side: superficial and deep masseter, medial pterygoid and digastric. The bite force tasks were performed on the ***right*** (affected) side.

The muscle patterns which seem to be abnormal as compared to the corresponding ones in the normal group showed that the working masseter and balancing temporalis were possibly less used. The clinical examination and the EMG muscle patterns consistently indicated that the working masseter was painful and rather inactive. The EMG data showed that the working masseter was particularly inactive for the 20° forward bite force (Figure 29B, *p*.225). This is not surprising because the data of the normal subjects revealed that a forward bite force demanded great activity from the working masseter. It seems probable that because the working masseter was suffering from pain, it was only slightly recruited even for the (forward) direction which is in its mechanically favorable line of action. This problem might have been aggravated by the tenderness of the right medial pterygoid which probably also contributed less to the 20° forward bite force. By the same token, other muscles (the working temporalis and balancing masseter) had higher than normal activity to compensate for the inability of the working masseter. The EMG data showed that the balancing temporalis was also less recruited. However, the left temporalis was not found to be painful clinically and this observation remains difficult to explain.

The direction chosen by this subject to produce maximum bite force was also peculiar: an angle of -6°, -20° (F-B angle and L-R angle in Figure 8, *p*. 184) might be accounted for by the unwillingness of the subject to use the painful masseter which, if used, would likely have directed the bite force more anteriorly. On the other hand, it might be argued that the painful medial pterygoid would conflict with the 6° medial component in the MVBF direction, but this slight medial angle may be related to the fact that the lower first molar is medially tilted.

5.I.10.a.(2)...Case II

The muscles which were clinically found to be tender were all on the ***left*** side: masseter, lateral pterygoid, posterior temporalis and digastric. The ***right*** (unaffected) side was chosen to perform bite force tasks.

Compared to the normal group, the possibly abnormal muscle ratios showed that the balancing (left) masseter, the balancing temporalis and the working masseter were less used. The left masseter was found to be rather inactive performing most tasks: vertical, 20° forward and 20° backward tasks; among these, the ratio increased the most for performing the 20° forward bite force. This seems to reflect the inability of recruiting the working masseter for this particular task which normally demands much activity from this muscle. Thus, it seems very probable that the left masseter was injured and being protected from being used. The EMG data also showed that the balancing (left) anterior temporalis was less used when it was compared to the working (right) temporalis for the 20° medial bite. The clinical data, on the other hand, showed that the left posterior temporalis was tender. The correlation between the two is not clear. The experimental results showed that the right masseter was even less active than the left masseter and this was contradictory to the clinical findings.

The MVBF on the right side was mainly medially directed (13°); this does not seem to conflict with the EMG finding that the right masseter was somewhat inactive.

5.I.10.a.(3)...Case V

Case V was impressive during both clinical examination and the experiment. Both examiners identified the right deep masseter as the only tender muscle. This subject had a peak MVBF on the right side as 740 *N* (average: 600 *N* during about

4 seconds). This MVBF was extraordinarily high among TMD subjects and is considered rather high among normal subjects (*c.f.* Table 3, *p*. 165). The direction of MVBF on the right side was -7°, -8° (F-B and L-R angles in Figure 8, *p*. 184); this direction might have been chosen to avoid using the right deep masseter whose line of action is somewhat vertical. EMG muscle patterns seem to suggest that the four tested jaw muscles, which did not include the painful right deep masseter, contracted similarly to those of the normal group except for the ratio of working (right) masseter over balancing (left) masseter for a 20° backward bite force. This abnormal ratio seems to indicate that the right superficial masseter had rather low activity. But the deep masseter was tender to palpation. Ignoring this ratio, it might be concluded that the activity patterns of all the jaw muscles of this subjects are consistent with those of the normal group.

5.I.10.a.(4)...Case VI

In Case VI, superficial and deep masseters, medial pterygoid and posterior digastric on the left side were found to be tender clinically. The tasks were performed on the left (affected) side. The EMG data showed that the working (left) temporalis and the balancing (right) masseter were less used. The experimental results do not seem to agree with clinical findings. However, the directions chosen by this subject to produce MVBFs are worth analysing. The direction for MVBF on the left (affected) side was 10°, 19° (F-B and L-R angles in Figure 8, *p*. 184). This angle seems to support that both deep masseter and temporalis on the right side were not used for producing this MVBF; the deep masseter was identified clinically and temporalis was identified by EMG muscle patterns. The direction for MVBF on the right (unaffected) side was 2°, 16° (F-B and L-R angles in Figure 8, *p*. 184). The 16° to the lateral is certainly peculiar as all the normal subjects found it difficult to bite laterally and this angle does not seem to conflict with the EMG finding that the right superficial masseter was in pain. Furthermore, this lateral angle, rather than a medial angle, also appears to be chosen because it might have involved less effort of contralateral muscle. Whether or not this peculiar lateral angle itself is sufficient to tell that a patient has muscle problems would be interesting to know.

5.I.10.b...Complex pain cases

Case III and IV are both considered as complex pain cases because these two subjects had pain/tenderness in most head and neck muscles bilaterally.

5.I.10.b.(1)...Case III

Case III was associated with tenderness in almost all the muscles on both sides. It was important to note that bilateral superficial masseters were more painful than others. Tasks were performed on the ***left*** side of the jaw in Case III.

The experimental data seem to suggest that the following muscles were less used: (1) the working masseter for the vertical, 20° forward, backward and medial bite forces; (2) the working temporalis for the 20° lateral bite force; (3) the balancing masseter for the vertical and 20° backward bite forces; (4) the balancing temporalis for the 20° medial bite force.

The left (working) masseter was consistently identified as being rather inactive when it was compared to the balancing masseter, and working temporalis except for the 20° lateral bite force. In the normal group, lateral bite force involved the greatest activity of working temporalis when it is proportionally compared to that of the working masseter. The clinical data also seem to indicate that both masseters were more tender than others. It seems possible that since the working masseter was more painful, the working temporalis was inevitably used for all the other directions until it was demanded for the lateral bite force which might have triggered the nociceptors of the working temporalis and, through negative feedback, inhibited its activity. The situation was similar for the balancing masseter and temporalis. However, since the working muscles were found to be even less active than the balancing muscles, such a phenomenon was more significantly associated with working side muscles. The direction of the MVBF on the left side was mainly posterior (10°) and might be accounted for by the postulate that the patient was unwilling to use the working masseter.

In summary, the EMG muscle patterns seem to indicate that muscle inability was extensive and the two (superficial) masseters were inactive for most tasks. The experimental findings seem to agree moderately well with the clinical examination.

5.I.10.b.(2)...Case IV

Case IV was represented by tenderness in the following muscles on the ***right*** side: (1) anterior and posterior temporal muscles, masseter and lateral pterygoid on the left and (2) medial and lateral pterygoids, temporalis insertion and digastric on the right side. The left side muscles which were tender include the anterior and posterior temporal muscles, the superficial masseters and lateral pterygoid. Tasks were performed on the ***right*** side of the jaw.

The EMG muscle patterns suggested that the following muscles might have had rather low activity: (1) the working (right) temporalis; (2) the working (right) masseter; and (3) the balancing (left) temporalis and the balancing masseter. That the working temporalis and working masseter were used to reduced extent agrees with the clinical findings. Balancing (left) temporalis was identified as being tender and so was the left masseter. The greater activity of the left masseter than temporalis might be because for the forward bite forces, masseter was still more preferably used due to its more favorable line of action although recruiting either was painful. The insertion of the right temporalis was painful. The conceivably healthy right masseter was probably responsible for the extra activity than the right temporalis for the forward bite forces. For 20° medial bite forces, the ratio of balancing temporalis over balancing masseter was abnormally high; the ratio of working over balancing temporal muscles was abnormally low. These two ratios seem to suggest that working temporalis and balancing masseter were abnormally inactive; this is in agreement with above findings.

5.I.10.c...Summary

It has been generally believed that painful jaw muscles are hyperactive while maintaining mandibular posture (*e.g.* Moller, 1985), but this view is not well accepted (Lund *et al.*, 1989). The behavior of painful jaw muscles during contraction, on the other hand, has received less attention.

In the present study, it was proposed that an injured jaw muscle would be protected and 'prevented' from contracting during some standard static tasks. This hypothesis is different from the so called 'protective muscle splinting' (Tally *et al.*, 1990) which is used to describe a 'guarded' closing muscle during jaw movement (mainly opening movement). However, the concept of 'protective muscle splinting' is rather new and, to the author's knowledge, it has only been tested once by Nielsen *et al.* (1990) in which those jaw muscles (masseter, temporalis and some jaw opening muscles) tender to palpation had lower activity while executing mandibular movements. Results obtained from TMD subjects in the present study seem to indicate that those jaw closing muscles tender to palpation may correspond to some abnormal muscle patterns which revealed their reduced activity compared to normal subjects. The reduced EMG activity of painful jaw muscles in TMD subjects seem to be supported by Kroon and Naeije (1992) who found that the EMG activity of painful TMD jaw muscles is less than that of the non-painful jaw muscles of the same subject. It is not known whether reduced muscle activity would lead to reduced cross-sectional area of the muscle in the long run.

Due to the lack of other sources with which the EMG data can be compared, the muscle patterns obtained from TMD patients have been compared with those of the corresponding ones obtained from the normal group and the clinical findings. It is obvious that the TMD muscle patterns indicating possibly inactive muscles do not always conform with the muscles tender to palpation in clinical examination although in some cases, the two sources were very consistent. It is recognized, however, that clinical examinations partially depend upon the subjective response from patients. In addition, pain may be referred to a different location (Christensen, 1981; Rasmussen, 1965).

Howell *et al.* (1986) and Jones *et al.* (1987) both suggested that painful muscles are electrically silent. These results, among others, may provide the physiological foundation for the reduced activity of the painful (and possibly injured) muscles in the present study. As a general view, the reflex pathway seems to be through type III (Aδ) or type IV (C) nerve fibers while the nerve endings are believed in the myotendinous junctions and fascial sheaths (Jones and Round, 1990).

Chapter 5, Section II

CONCLUSIONS

The following conclusions are drawn from the present study.

(1) The force transducer developed for the present study can be used to measure 1) the real magnitude of a static bite force as compared to the single component of the bite force measured with a uni-directional force transducer and 2) the direction of a bite force in three dimensional space. Although some aspects of the force transducer may be improved, it has been validated by revealing consistent results comparable to another source (van Eijden *et al.*, 1988a and 1990) and by showing a change in the bite force direction during sustained contraction of jaw muscles (Osborn and Mao, 1992).

(2) There appears to be approximate linearity between the increase in the surface EMG activity of the bilateral superficial masseter and anterior temporal muscles and the graded bite force in each of the five directions studied (the vertical and 20° forward, backward, medial and lateral from the vertical and in 90° intervals in the horizontal plane) with few exceptions. Such approximate linearity between muscle tensions and bite forces in various directions seems to indicate that an alteration in the force direction will not change the classic EMG-force relationship.

(3) Muscle tensions expressed as linear regression lines for bite force tasks performed on the left side of the jaw show mirror images for the same tasks performed on the right side of the jaw. This indicates that jaw muscles on the left and right sides are generally symmetrical. This further validates the force transducer and EMG recordings.

(4) The relative contribution, to a bite force, of certain jaw closing muscles is constant as long as the direction of the bite force is fixed; this is true regardless of the magnitude of the bite force to a certain submaximal level.

(5) The ratios of EMG activity in jaw closing muscles appear to be specific for a fixed direction of a bite force. This, along with results from other studies, seems to indicate that the direction of a mechanical force produced by a group of synergistic muscles is as important controlled by the central nervous system as the magnitude of the force. The direction might have been chosen to minimize the magnitude in order to minimize the amount of energy used for a specific task.

(6) Methods used in the present study seem to be useful in exploring how synergistic muscles are used to perform static tasks.

(7) Muscle activity patterns in TMD subjects might be different from those measured in a normal group. Some of the differences seems to be sufficiently aberrant to be detected. These deviated muscle patterns may correspond to those tender jaw muscles identified clinically.

Table 1. Maximum incisal bite force.

Investigators	**Newtons (*kg*)**	**Note**
Dahlström *et al.* (1988)	158 (16)	force feedback
Hannam (1976)	87 (8.9)	anterior teeth
Helkimo *et al.* (1977)	176 (18) 108 (11)	Skolt Lapps male Skolt Lapps female
Helkimo and Ingervall (1978)	190 (19)	
Helle *et al.* (1983)	75 (7.6) to 178 (18)	children (<17 years)
Hellsing (1980)	185 (19)	
Linderholm and Wennström (1970)	216 (22) 196 (20)	male female
Ringqvist (1973*a*)	293 (30)	

Table 2. Maximum bite force on premolars.

Investigators	**Newtons (*kg*)**	**Note**
Dahlström *et al.* (1988)	662 (67)	force feedback
Linderholm and Wennström (1970)	410 (22) 350 (20)	male female
Molin (1972)	344 (35)	
Widmalm and Ericsson (1982)	181 (18) to 608 (62)	

Table 3. Maximum bite force on molars. Some values are averages and rounded off.

Investigators	**Newtons (*kg*)**	**Note**
Bakke *et al.* (1990)	522 (53) 441 (45)	male female
Flöystrand *et al.* (1982)	330 (37) to 680 (69)	male female
Hagberg *et al.* (1986)	357 (36) to 396 (40)	
Helkimo *et al.* (1977)	382 (39) 216 (22)	male female
Helle *et al.* (1983)	209 (21) to 406 (41)	children (<17 years) on M1 and E
Linderholm and Wennström (1970)	490 (50) 430 (44)	male female
Lindqvist and Ringqvist (1973)	463 (47)	in bruxists and controls
Proffit *et al.* (1983)	304 (31) 349 (36)	2.5 *mm* thick transducer 6 *mm* thick transducer
Ringqvist (1973*a*)	468 (48)	
Sasaki *et al.* (1989)	189 (19)	

Table 4. Effects of local anesthesia on MVBF.

	Lund & Lamarre (1973)	van Steenberghe & de Vries (1978)	Orchardson & MacFarlane (1980)	Teenier *et al.* (1991)
Bite force	s.g. transducer	cantilever beam	cantilever beam	cantilever beam
Position	P1,2 (one side)	Left canines	C + P1 (one side)	Left M1s
Duration	5 *s*	?	5 *s*	2 *s*
Onset	rapid	slow	rapid	?
EMG	ipsilateral masseter + ant. temporalis	No.	No.	bilateral masseter + ant./post. temporalis
LA	4% Citanest	3% Citanest	4% prilocaine	2% lidocaine with epinephrine
LA methods	infiltration around roots	local infiltration	*upper*: infiltrated; *lower*: mental block	*upper*: infiltrated; *lower*: IDN block; long buccal nerve block
Duration	15 *min.*	?	20 - 25 *min.*	?
Results	MVBF dropped by 40%; EMG not conclusive	increased MVBF	increased MVBF	No change in MVBF and EMGs

Table 5. Accuracy of the force transducers during calibration.

Actual angle		Predicted angle (Black)*			PPredicted angle (Blue)*			Predicted angle (Red)*			Predicted angle (Purple)*		
p	q	P	Q	Kg	P	Q	Kg	P	Q	Kg	P	Q	Kg
0	-30	-6	-29	9.8	3	-29	9.2	-1	-29	9.6	0	-32	9.8
0	-15	-3	-17	10.1	-1	-20	10.3	1	-19	10.1	-3	-15	10.6
0	0	-3	+2	10.2	-1	2	10.4	0	0	10.1	-1	-1	10.1
0	15	+2	16	10.1	-1	16	10.4	1	25	11.1	-5	15	10
0	30	-1	30	9.5	2	31	10.3	1	24	9.9	0	32	9.4
-30	0	-29	-1	10.5	-32	1	9.8	-30	-1	10.3	-26	-2	9.4
-15	0	-16	-1	10.5	-15	2	10.5	-17	0	10.9	-19	0	9.9
0	0	-3	-1	10.2	-1	2	10.4	0	0	10.1	-1	-1	10.1
15	0	19	-1	9.9	14	1	10.5	19	-2	10	12	0	9.6
30	0	29	1	9.5	32	1	9.9	27	-2	10.2	33	-1	9.6
-15	-15	-16	-13	10.5	-12	-18	10.1	-17	-16	10.6	-10	-13	10.3
15	-15	10	-17	10.2	12	-18	10.5	16	-20	10.2	4	-13	10.4
-15	15	-16	13	10.8	-12	18	10.7	-16	15	10.8	-16	12	10.1
15	15	5	13	10.1	12	18	10.8	17	15	10.1	8	14	9.7

*: names for different transducers.

Table 6. Correlation coefficients (r values) between bite force increments in different directions and averaged EMG activity: means and standard deviations (S.D.).

	Mean	S.D.	N
Forward bites	0.82	0.21	34
Backward bites	0.85	0.19	23
Vertical bites	0.88	0.13	39
Medial bites	0.91	0.07	36
Lateral bites	0.86	0.25	11
Overall	0.87	0.17	143

Figure 1

Housing of the bite force transducer

The housing of the bite force transducer used for the studies in this thesis had a hollow **H** shape.

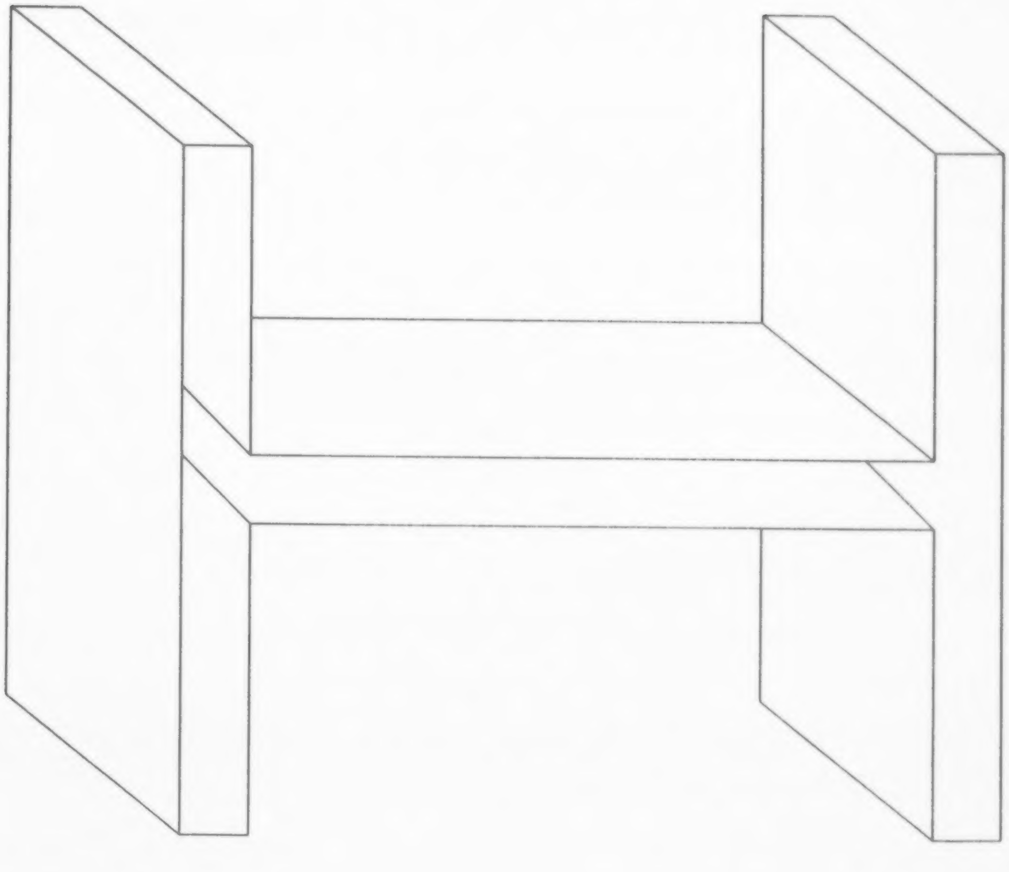
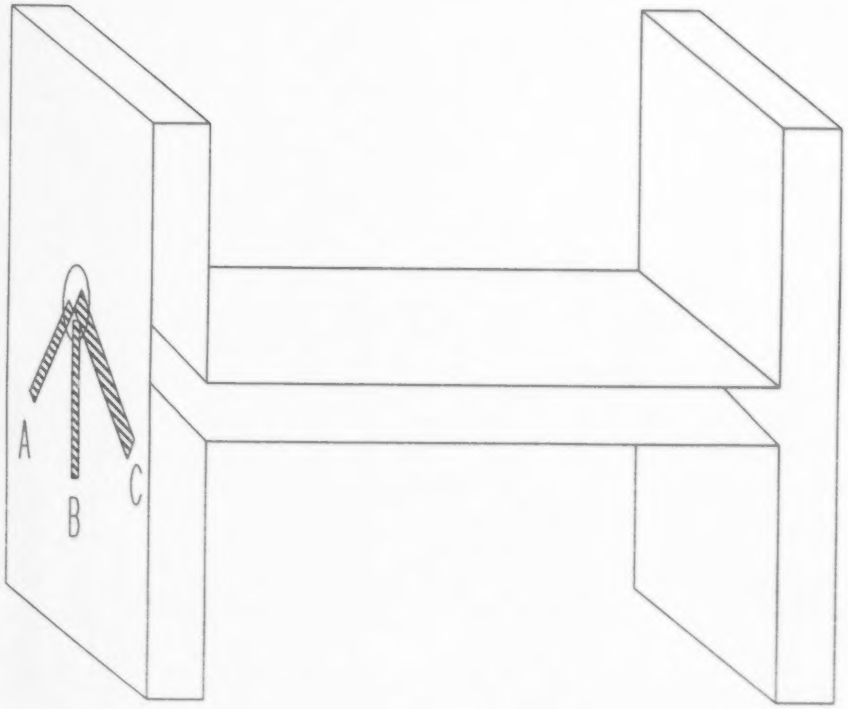


Figure 2

The bite force transducer: housing and sensors

The **H**-shaped housing allowed the sensors to be placed on the two vertical plates rather than in the part of the force transducer between the upper and lower (occluding) teeth.

Stacked strain gauge rosettes were used as sensors. Three single strain gauges (A, B, and C) form a rectangular rosette in the factory. For each of the rectangular rosettes, three strain gauges are angled by 45° intervals. After the surface of the housing was prepared, two rosettes were installed on the outside vertical plates of the **H**.


A
B
C

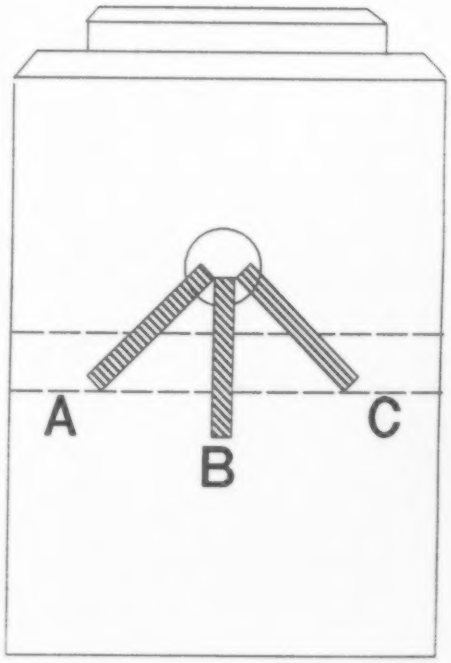

A
B
C

Figure 3

Parts of the housing

The material of the housing was made of the gauge #20 stainless steel plate. Four pieces of the stainless steel were cut or bent into the required shape to form the hollow H-shaped cross section. If the sensitivity and orientation of the sensor are fixed, stainless steel with lower gauge numbers (thicker and therefore more rigid) reduces the sensitivity of the force transducer.

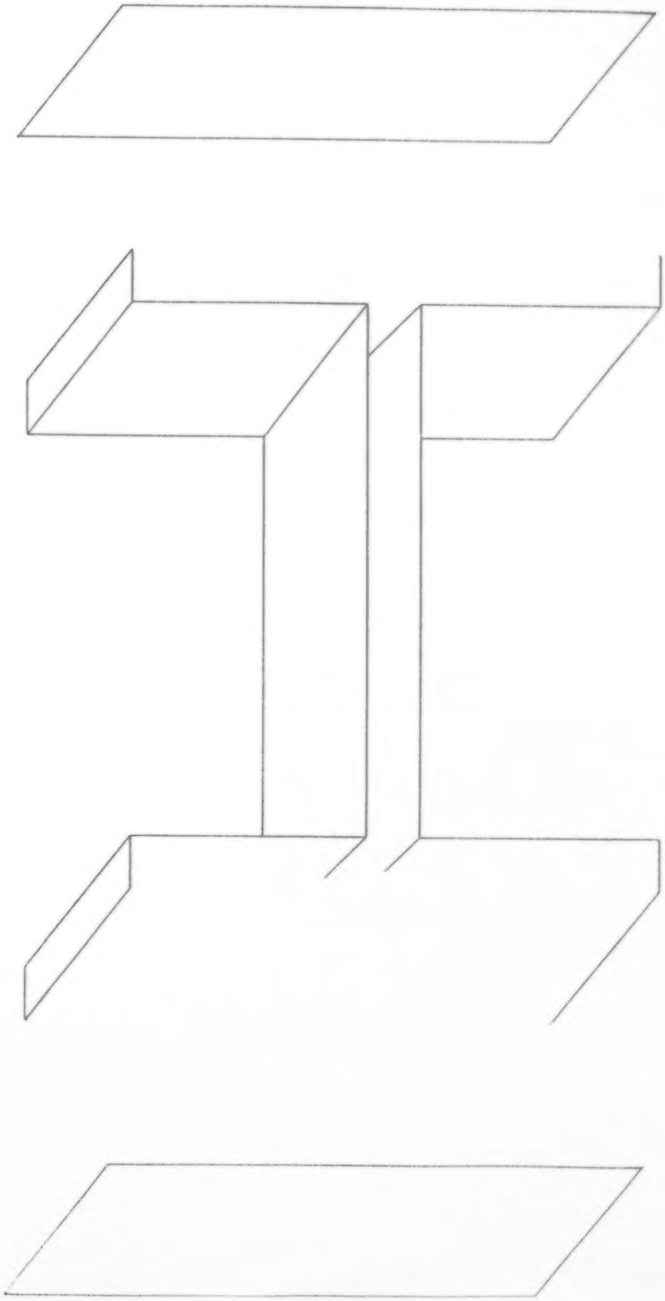


Figure 4

Dimensions of the force transducer

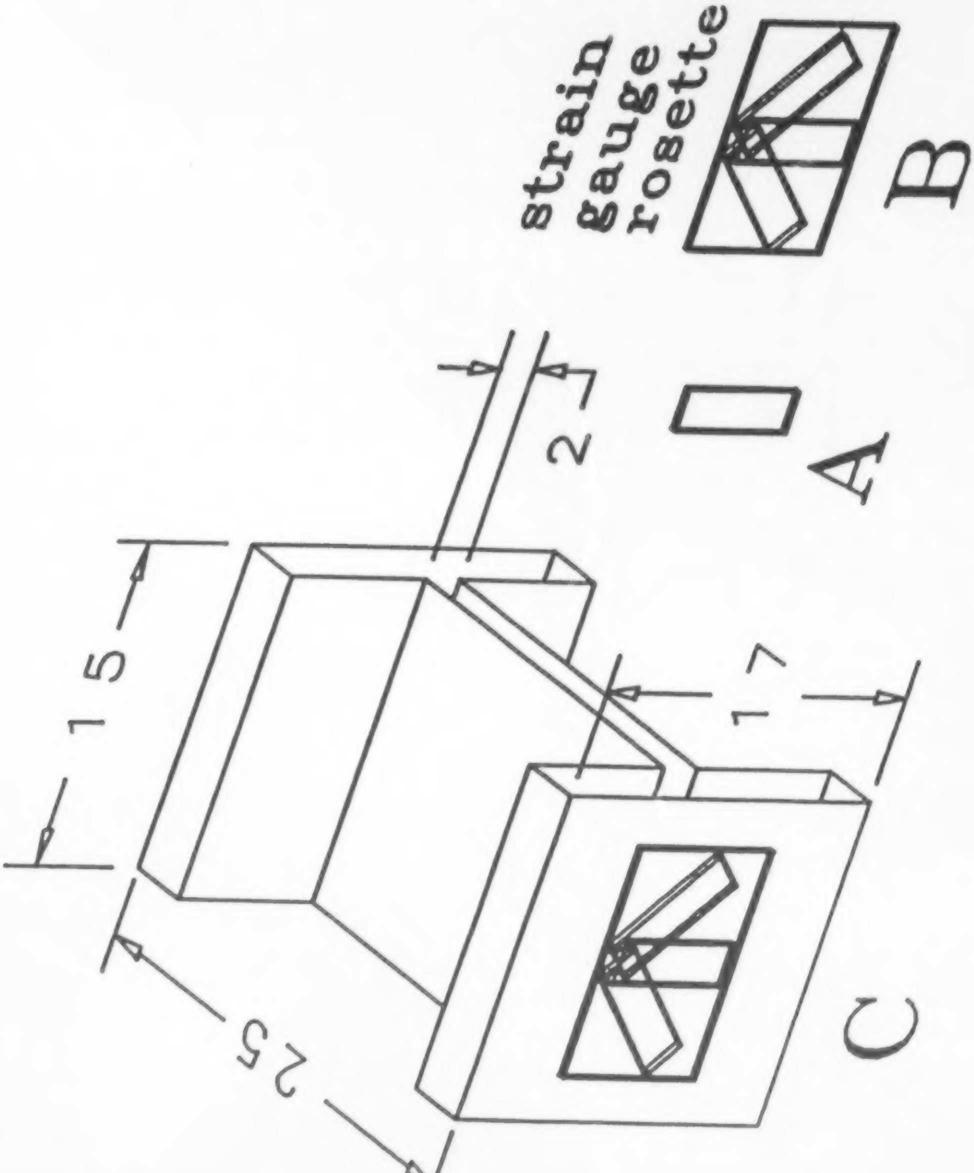

strain gauge rosette
B
A
2
15
17
25
C

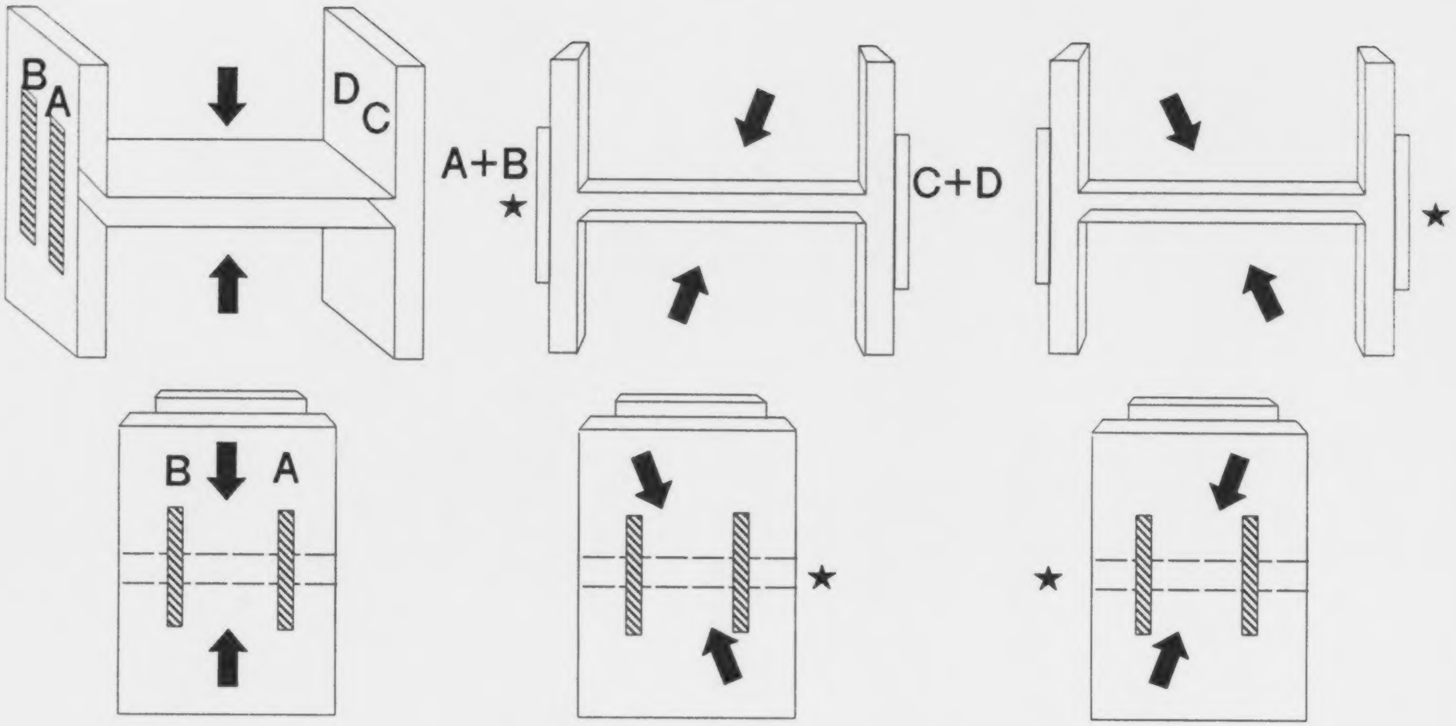
Figure 5

Vertically oriented single strain gauges

Four identical single strain gauges (CEA-13-062UW-350) were first chosen as sensors. These four gauges were installed upright on the two vertical plates of the **H** shaped housing; two gauges on the same plate were parallel to each other and separated by about 8 *mm*.

Arrows represent the direction of the force applied during calibration and a star represents the plane or the strain gauge which is stressed more than its opposite. A, B, C and D represent the four strain gauges.

This four vertical gauge configuration was excellent for distinguishing changing directions of forces in the frontal plane (from side to side) but was not sufficiently sensitive for those in the sagittal plane (from anterior to posterior). Therefore, this configuration was abandoned. The insensitivity in the sagittal plane might be because the two vertically oriented strain gauges on the same plate were too close to each other to detect differences in the altering directions of forces in the sagittal plane.


B
A
D
C
A+B
★
C+D
★
B
A
★
★

8 mm between A and B

Figure 6

Wheatstone bridge: 1/4 bridge configuration

A Wheatstone bridge circuit is shown with 1/4 bridge configuration. The 1/4 configuration enables every gauge in the circuit to be actively involved in measuring stress and to yield its own strain output. The independent performance of each gauge was critical for distinguishing the direction of a force.

Each strain gauge in the two rosettes was one of the four components of one Wheatstone bridge circuit and was considered a resistor. R2, R3 and R4 were the other three resistors. The circuit was balanced out by alternating R_4. V_e was the source of an excitation voltage (3 *V*) supplied to each gauge (channel). V_{out} was the readout.

Strain due to temperature variation (apparent strain) was compensated by the fact that the strain gauge rosettes used in the present study were self-temperature-compensated gauges which are stable to temperature variation within the working range.

Strain Gauge and Wheatstone Bridge

1/4 bridge configaration

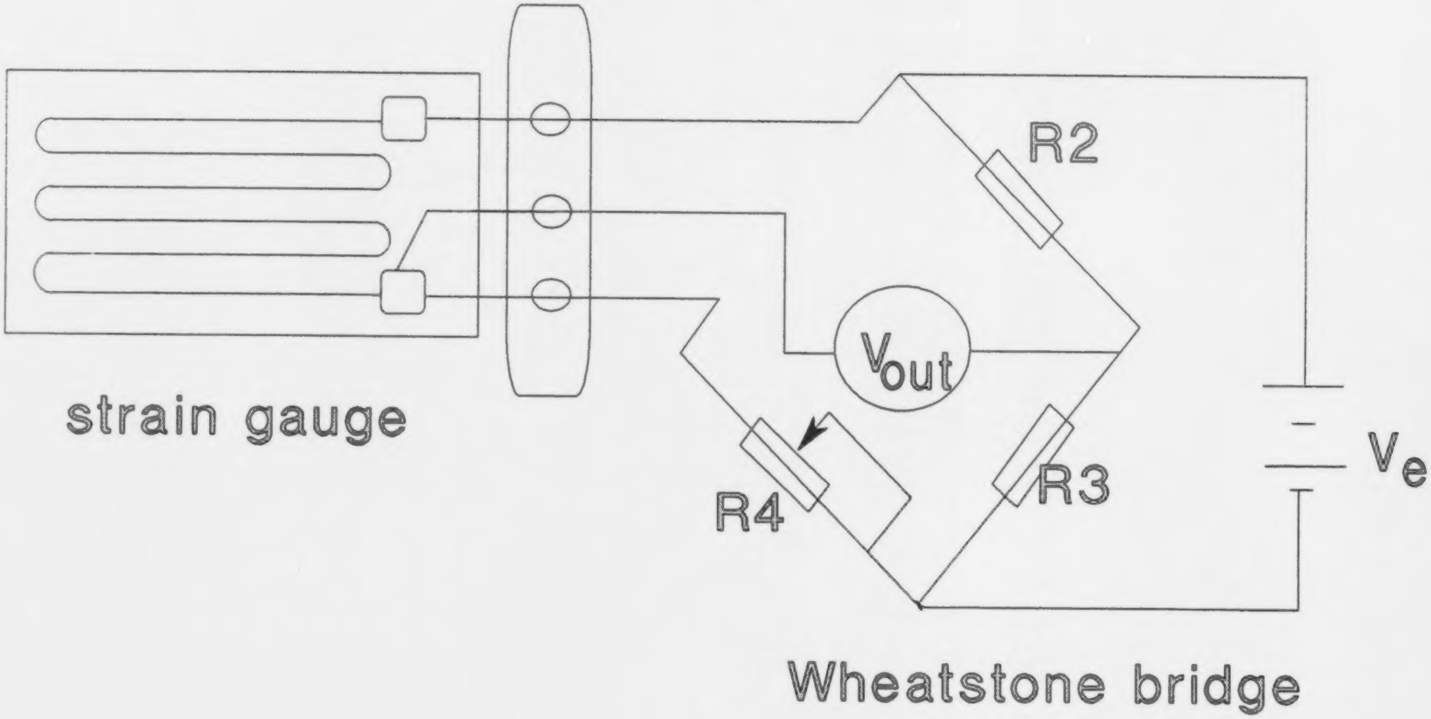

strain gauge
R2
V_{out}
R3
R4
V_e
Wheatstone bridge

Figure 7

Force transducer calibration

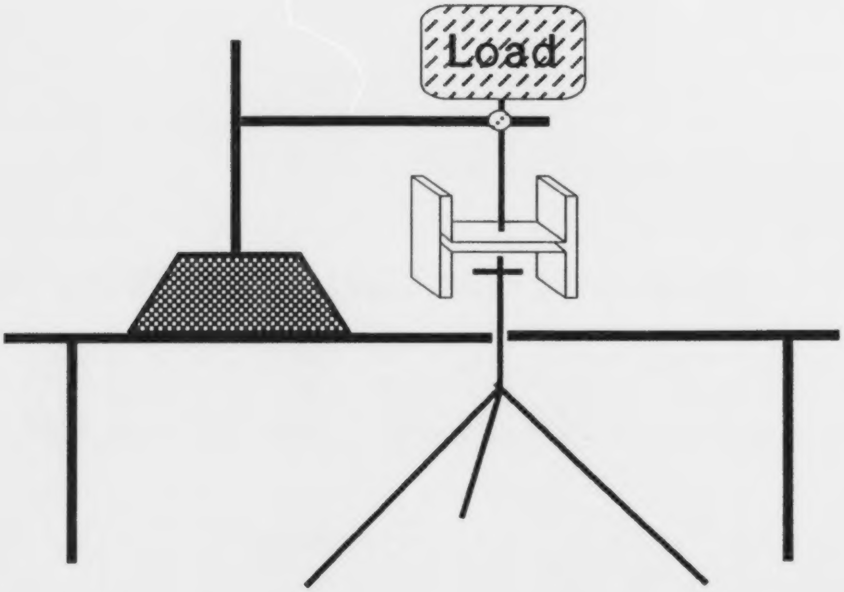
A metal camera tripod was used as the base for holding the force transducer during calibration. Thin layers of quick-set acrylic were placed in the upper and lower recesses of the **H**. Before the acrylic was set, a bolt was placed in the center of the lower acrylic block and a small hole, for location purposes, was put in the center of the upper acrylic block. After both pieces of the acrylic became solid, the whole transducer was screwed onto the camera tripod. A pin held by a vice served as the pointer (down to the hole in the center of the upper acrylic block) through which standard loads were applied.

The standard loads used to apply forces were brass weights from 10 *N* to 150 *N*. The directions of the forces applied as loads were 0°, 15° and 30° away from the vertical (to the ground) at 45° intervals around the full 360° in the horizontal plane.

A change in the direction of force was made possible by changing the angle of the head of the tripod. When a load was applied to the cross bar of the **H**, the vertical plates of the **H** were deformed along with the strain gauges installed to them.

Figure 7A shows the force transducer was placed horizontally, while the transducer was tilted to about 30° to the left and 30° forward in Figure 7B.

A



B

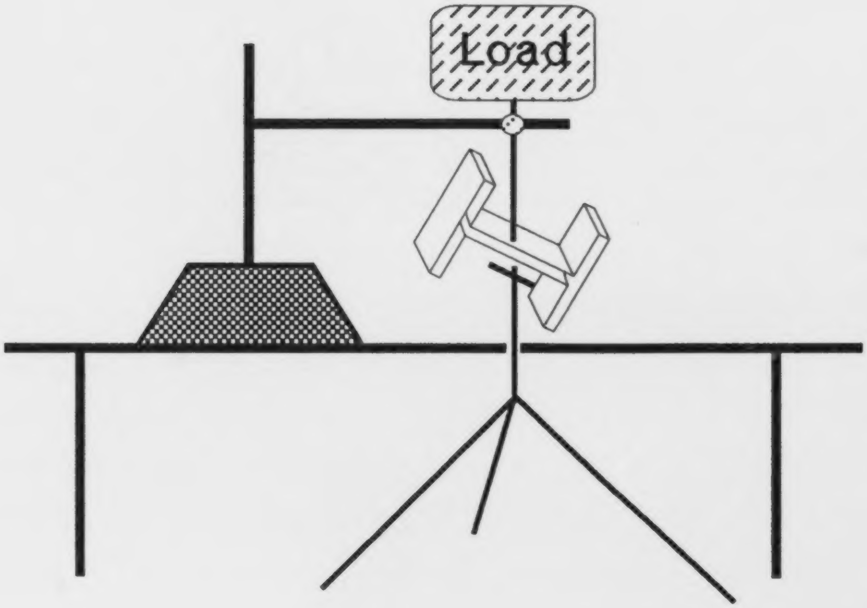


Figure 8

Visual feedback of bite force magnitude and direction

The display on the computer video screen seen by a subject when set to perform a given bite force task. The center of the coordinate system represented a vertical bite force. Each of the three large concentric circles represented angles at 10° intervals away from vertical. The *target circle* (the small circle between the 10° and 20° concentric circles) showed the direction of a required bite force specified by an experimenter. The small filled circle represented the actual direction in which the subject was biting and moved around as the direction of the bite force changed. It was falling inside the *target circle* as shown in this case and a subject was producing a 22 *kg* bite force with a direction of +15 and +5. The magnitude of the bite force actually being produced by a subject was constantly being displayed on the vertical scale at the right. The actual values of the magnitude and two angles (forward/backward, left/right) of the bite force were shown at the bottom left. The readings from the six strain gauges (in microstrains) were constantly scrolling at the bottom of the screen.

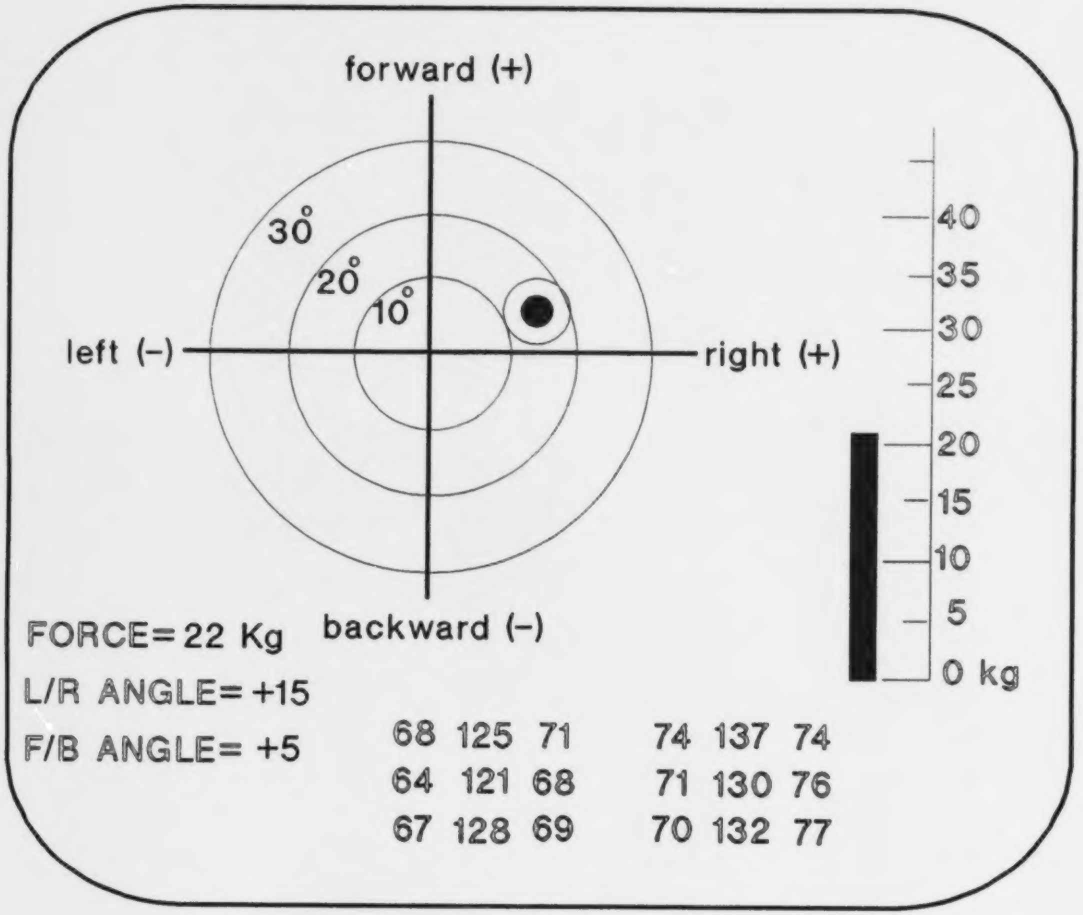

forward (+)
30°
20°
10°
left (–)
right (+)
backward (–)
40
35
30
25
20
15
10
5
0 kg
FORCE= 22 Kg
L/R ANGLE= +15
F/B ANGLE= +5
68 125 71
64 121 68
67 128 69
74 137 74
71 130 76
70 132 77

Figure 9

The bite force transducer *in situ*: jaw separation

After the bite force transducer was installed between the upper and lower first molars, jaw separation measured as the inter-incisal distance was 4 to 6 *mm*.

Figure 9(i): a sagittal view of the upper and lower jaws and the resulting thickness after the force transducer was installed between one pair of occluding first molars;

Figure 9(ii): a frontal view under the same condition;

Figure 9(iii): also a frontal view of the transducer between one pair of occluding molars with the upper and lower acrylic blocks. The upper and lower pieces of acrylic provided stable and, more importantly, reproducible bases for the upper and lower occluding teeth in the upper and lower recesses between the vertical arms of the **H** after the transducer was reinstalled.

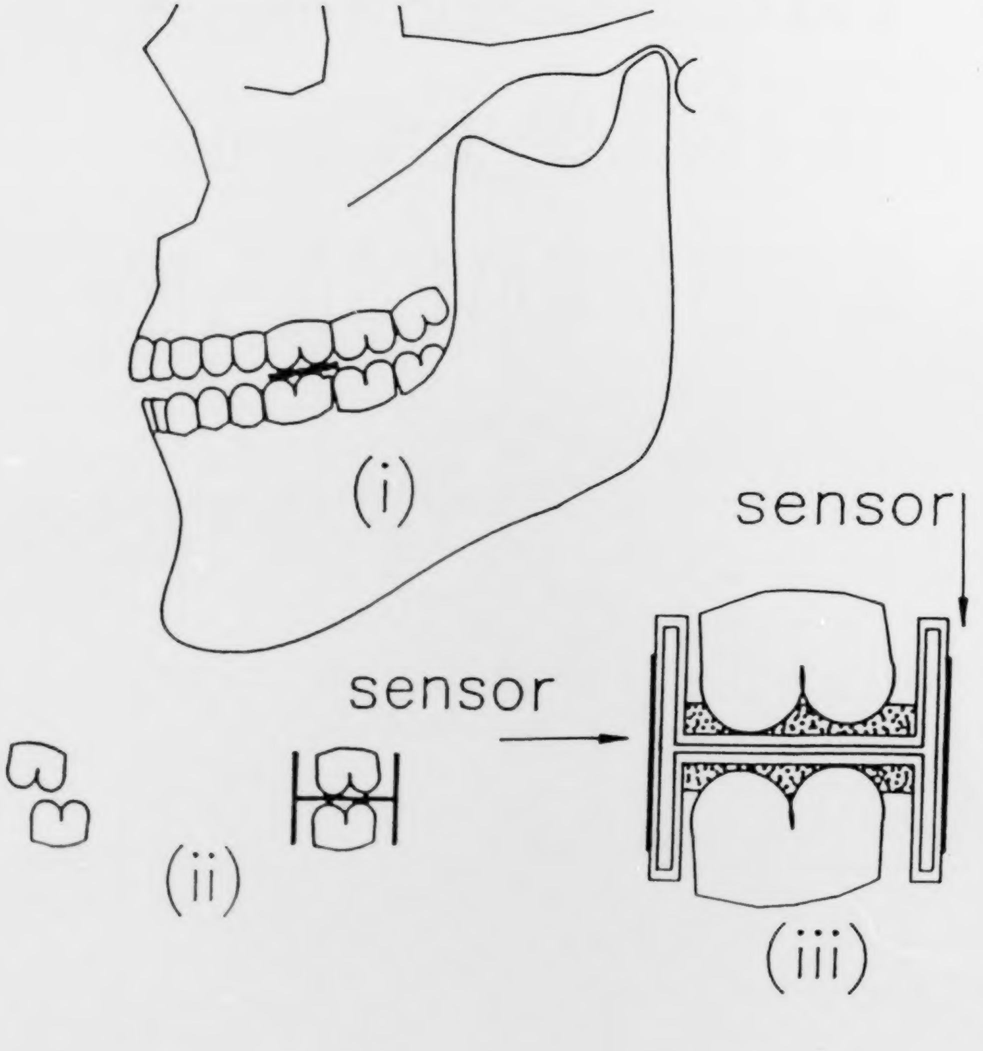

(i)
sensor
sensor
(ii)
(iii)

Figure 10

Flow diagram of the bite force recording devices

Stress detected by the bite force transducer was fed to the strain gauge conditioner card and then to a 12-bit analog/digital converter card. The digitized strain gauge data were originally recorded at 1 *Hz* onto the hard disk of an IBM XT computer. Later, an IBM compatible 386/25*MHz* computer (with mathematic co-processor) replaced the IBM XT and increased the sampling frequency to 10 *Hz*.

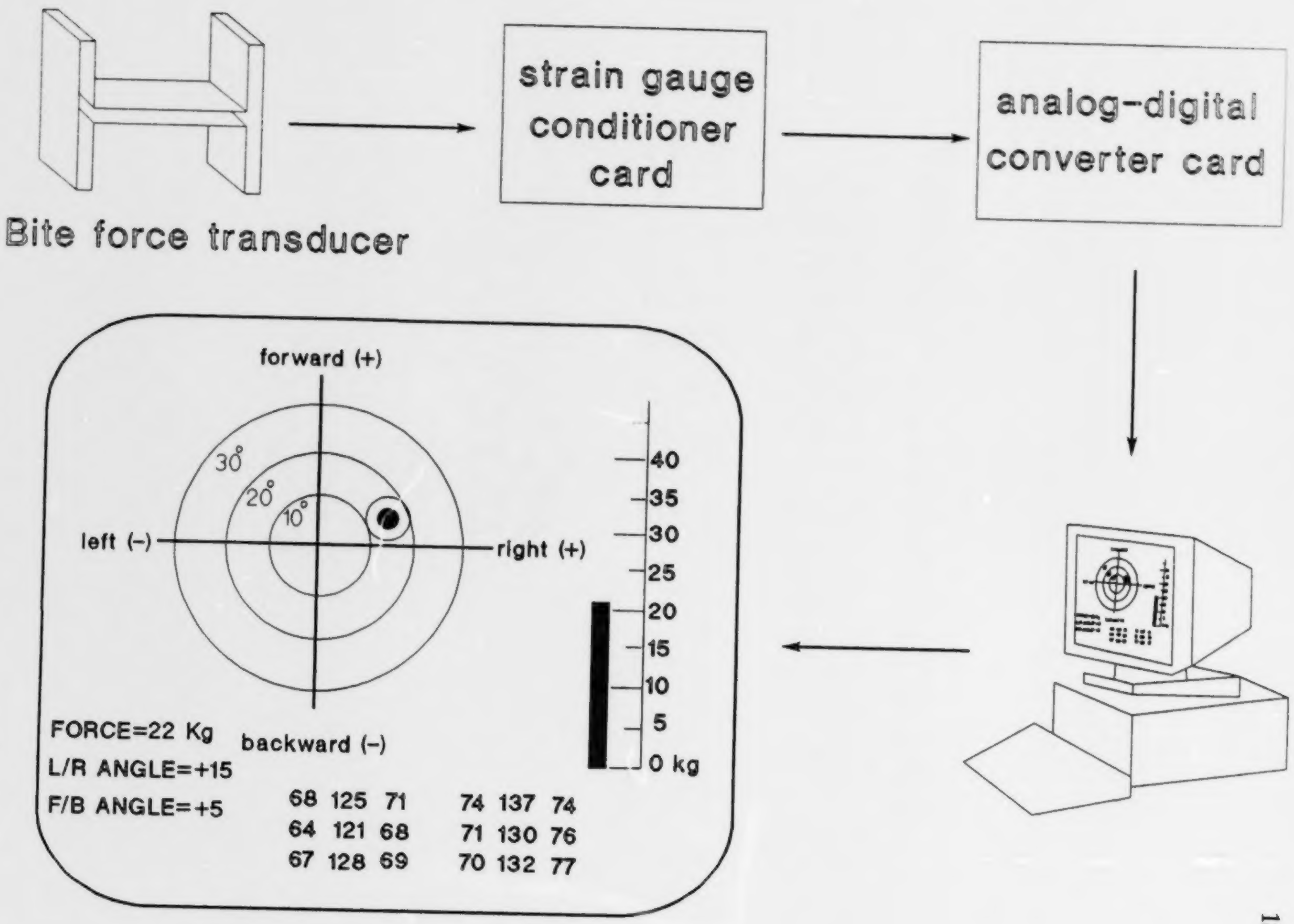

Bite force transducer
strain gauge conditioner card
analog-digital converter card
forward (+)
backward (–)
left (–)
right (+)
30°
20°
10°
40
35
30
25
20
15
10
5
0 kg
FORCE=22 Kg
L/R ANGLE=+15
F/B ANGLE=+5
68 125 71
64 121 68
67 128 69
74 137 74
71 130 76
70 132 77

Figure 11

Flow diagram of the EMG recording devices

The sequence of the four channels were consistent throughout all experiments: channel 1 being the right anterior temporalis; channel 2 the right superficial masseter; channel 3 the left superficial masseter and channel 4 the left anterior temporalis.

The 4-channel EMG signals were amplified with preamplifiers at a gain of 1,000 and with a bandwidth of 10 - 1,000 *Hz*. The low cut-off frequency was set at 10 *Hz* for future fast Fourier transform analysis. Occasionally, this low cut-off frequency was increased to 100 *Hz* due to, for example, 60 *Hz* AC contamination in the EMG signal. In this case, the file was marked accordingly.

The raw EMG signals were monitored on an oscilloscope and fed through a 12-*bit* analog/digital converter at 1,000 *Hz*/per channel. The digitized data were picked up by the data acquisition board installed in a personal computer (IBM compatible 486/33 *MHz* with a mathematic co-processor) and collected onto its hard disk (120 *Megabytes*). Recording duration for each task was 4.096 seconds; this unusual time, as a power of 2, was chosen for the convenience of fast Fourier Transform analysis.

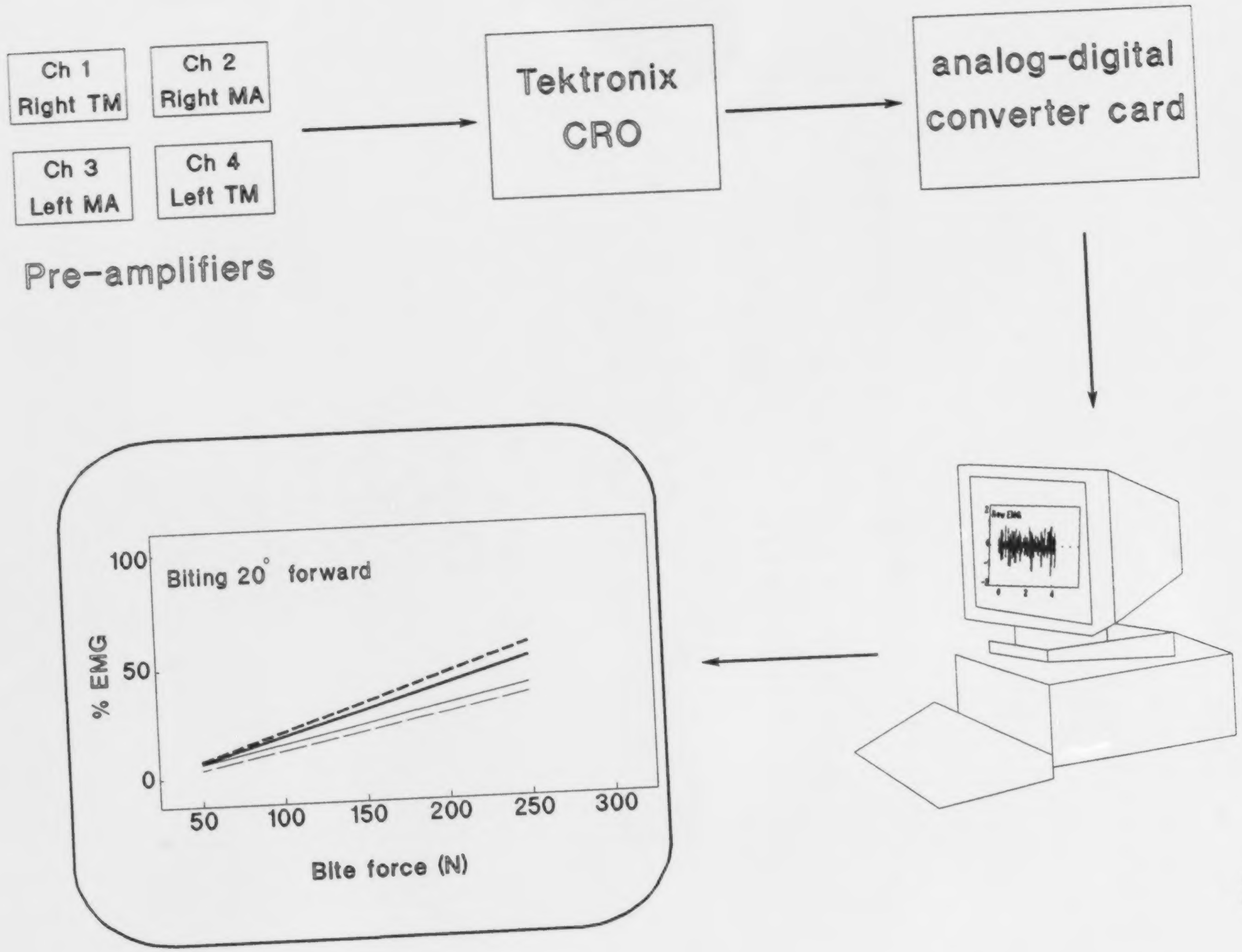

Ch 1
Right TM
Ch 2
Right MA
Ch 3
Left MA
Ch 4
Left TM
Pre-amplifiers
Tektronix
CRO
analog-digital
converter card
Biting 20° forward
% EMG
100
50
0
50
100
150
200
250
300
Bite force (N)

Figure 12

The raw, full-wave rectified, and integrated EMGs

A (the upper plot): raw EMG signal of a muscle under contraction: compound action potentials recorded with surface electrodes were extensively superimposed.

B (the middle plot): full-wave rectified EMG of the same signal: this procedure turned all the negative components of the raw EMG signal upwards to become positive.

C (the lower plot): integrated or smoothed EMG of the same signal: the rectified EMG data points were averaged over certain data point intervals.

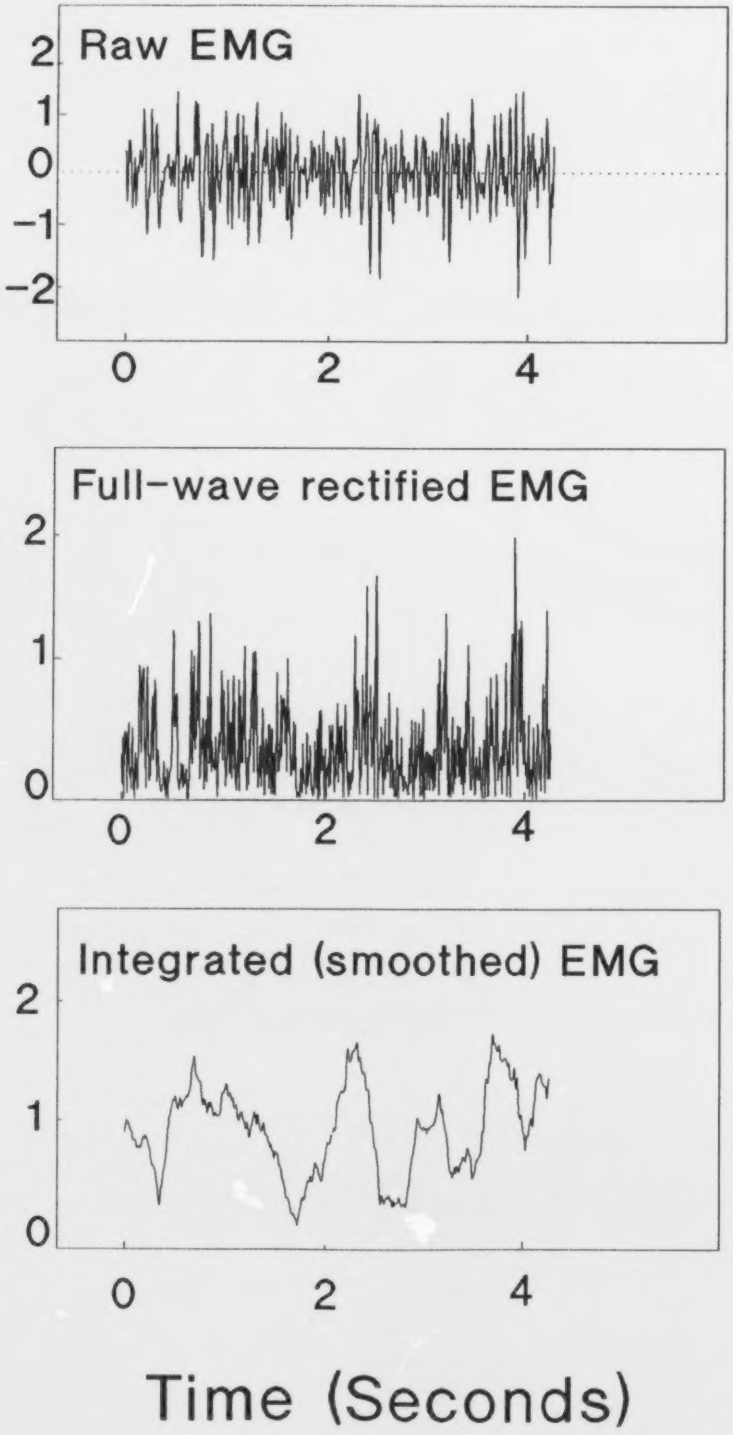

Raw EMG
2
1
0
−1
−2
0
2
4
Full-wave rectified EMG
2
1
0
0
2
4
Integrated (smoothed) EMG
2
1
0
0
2
4
Time (Seconds)

Figure 13

Raw EMG recording

This gives some rough idea of the signal-to-noise ratio (SNR) during EMG recording. The trace was randomly selected from many. The subject, about 1 second after the recording started, clenched a moderate force for about a second and then stopped clenching. After a 1-second interval, the subject resumed clenching with a similar duration.

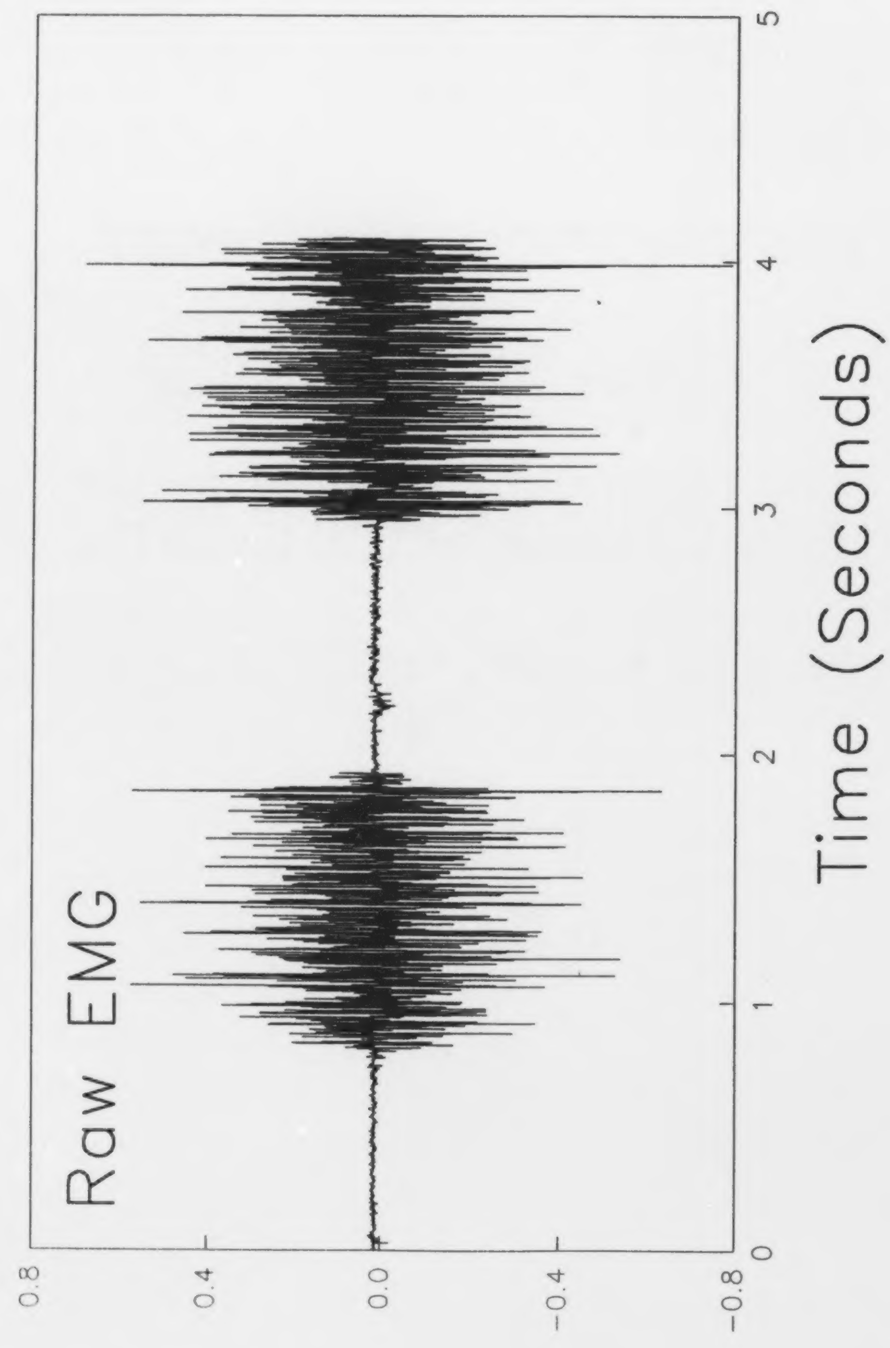

Raw EMG
0.8
0.4
0.0
-0.4
-0.8
0
1
2
3
4
5
Time (Seconds)

Figure 14

Dispersion of EMG data

The combination of the muscles and tasks for each of the four plots was randomly chosen. The obviously skewed data points include:

A

for the balancing masseter muscles of three subjects when biting vertically (symbolized as solid and open squares and solid upward triangles);

B

for the working masseter muscles of one subject during biting 20° medially (symbolized as solid upward triangles);

C

for the balancing temporalis of one subject during producing 20° backward bite forces (symbolized as empty upward triangles);

D

for the working temporalis of one subject (symbolized as solid squares) upon exerting 20° forward bites.

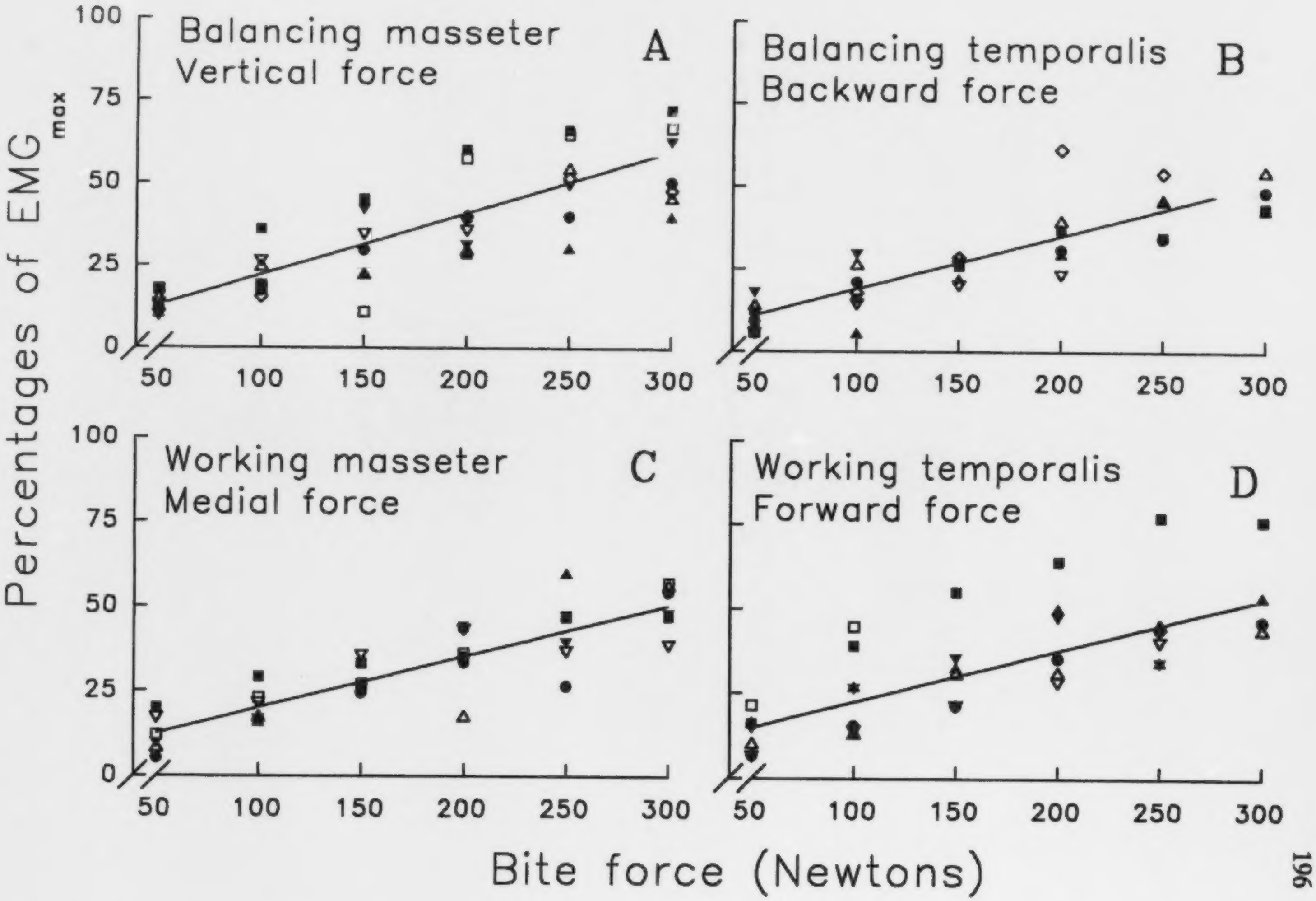

Percentages of EMG$_{max}$
Bite force (Newtons)
Balancing masseter
Vertical force
A
Balancing temporalis
Backward force
B
Working masseter
Medial force
C
Working temporalis
Forward force
D
0
25
50
75
100
50
100
150
200
250
300

Figure 15

EMG activity: bite force directions in the sagittal plane

TM: temporalis; MA: masseter. Integrated and normalized EMG was plotted against bite forces with their directions projected onto the sagittal plane. Each plot shows a linear regression line representing the averaged EMG data points of the same muscle of all subjects with vertical standard deviation bars. The bite force increments were considered the independent variable and the EMG activity the dependent variable. The slopes differ for different muscles and tasks. In general, a nearly linear relationship can be found between the graded bite force and the normalized surface EMG.

In the sagittal plane.

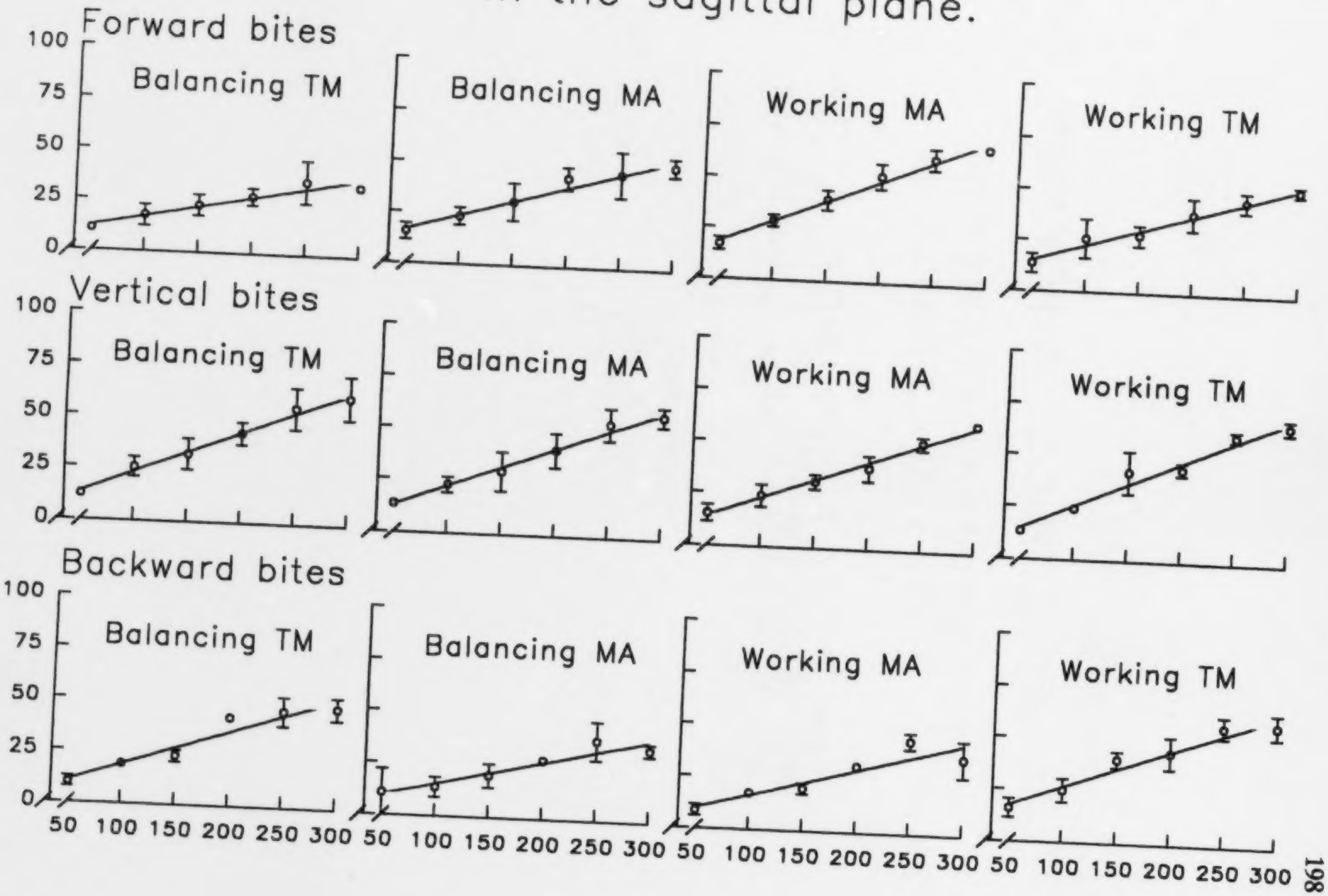


Figure 16

EMG activity: bite force directions in the frontal plane

TM: temporalis; MA: masseter. Integrated and normalized EMG was plotted against bite forces with their directions projected onto the frontal plane. Each plot shows a linear regression line representing the averaged EMG data points of the same muscle of all subjects with vertical standard deviations. The bite force increments were considered the independent variable and the EMG the dependent variable. The slopes are differing for different muscles and tasks. In general, a linear relationship can be found between the graded bite force and the normalized surface.

In the frontal plane.

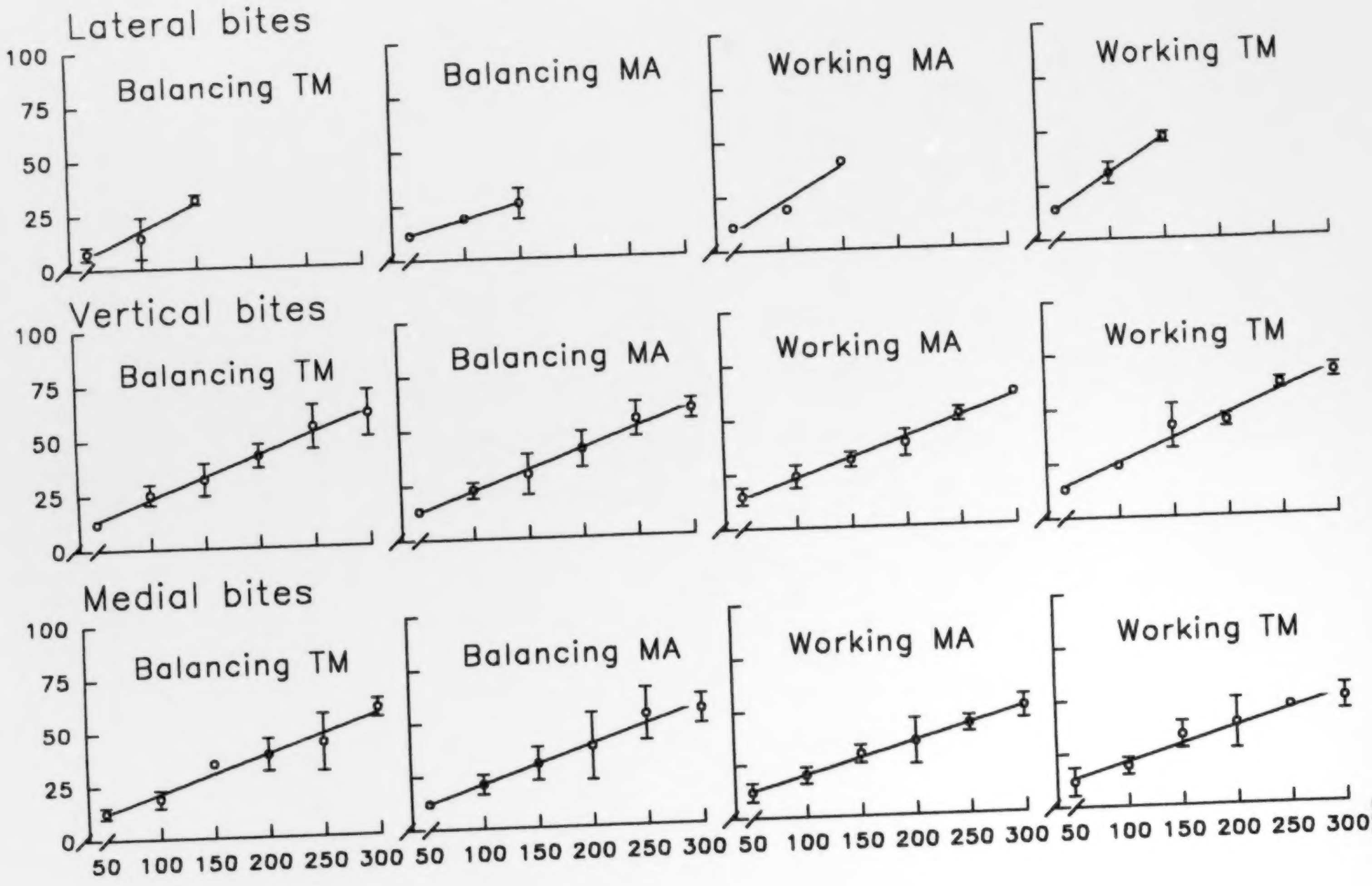


Figure 17

r values for 20° forward bite forces

TM: temporalis; MA: masseter. All the correlation coefficients (*r* values) were above 0.5 except for the balancing masseter of one subject. That *r* value was 0.36.

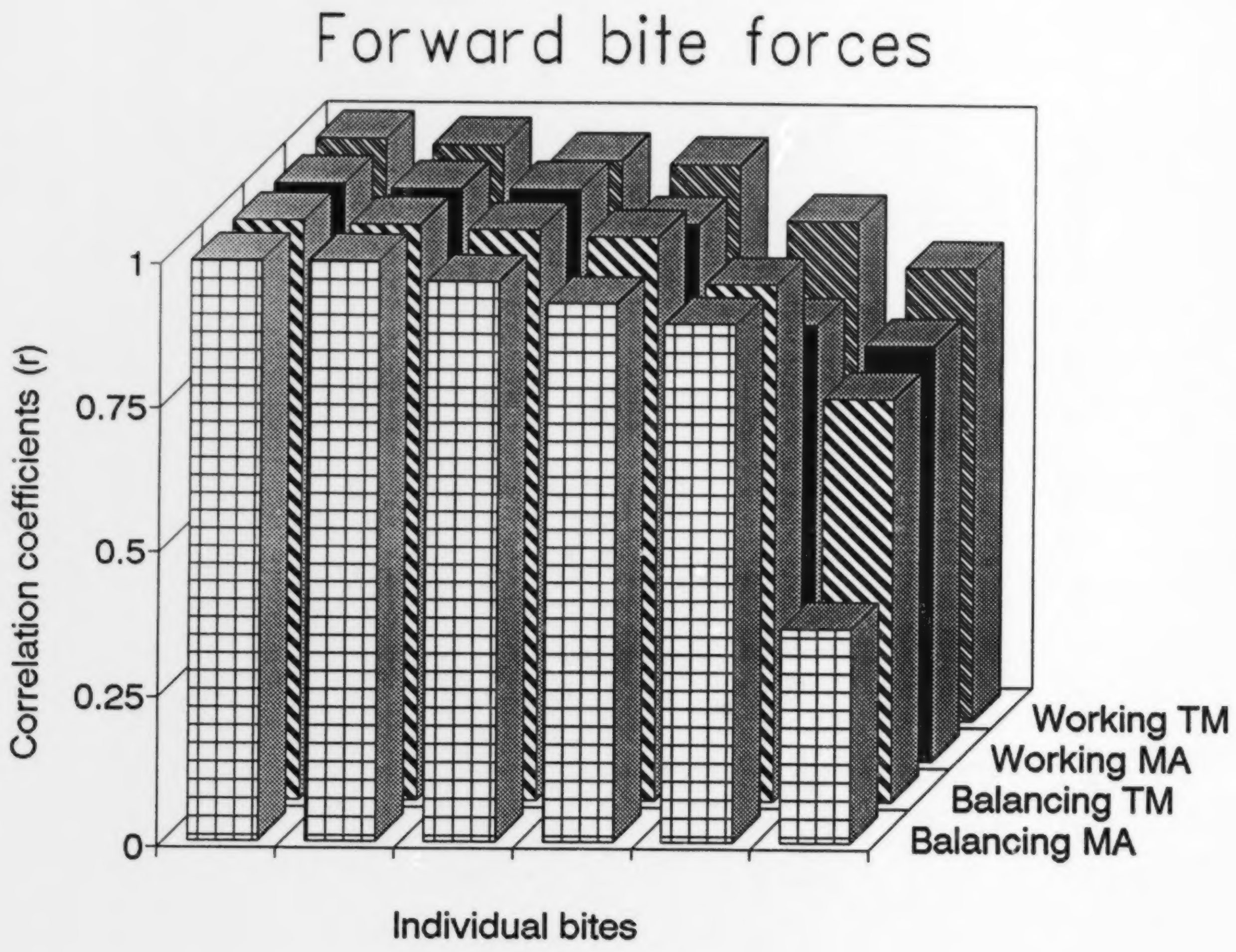

Forward bite forces
Correlation coefficients (r)
1
0.75
0.5
0.25
0
Individual bites
Working TM
Working MA
Balancing TM
Balancing MA

Figure 18

r values for 20° backward bite forces

TM: temporalis; MA: masseter. All the correlation coefficients (*r* values) were above 0.5 except for the balancing masseter of one subject. This value was 0.49.

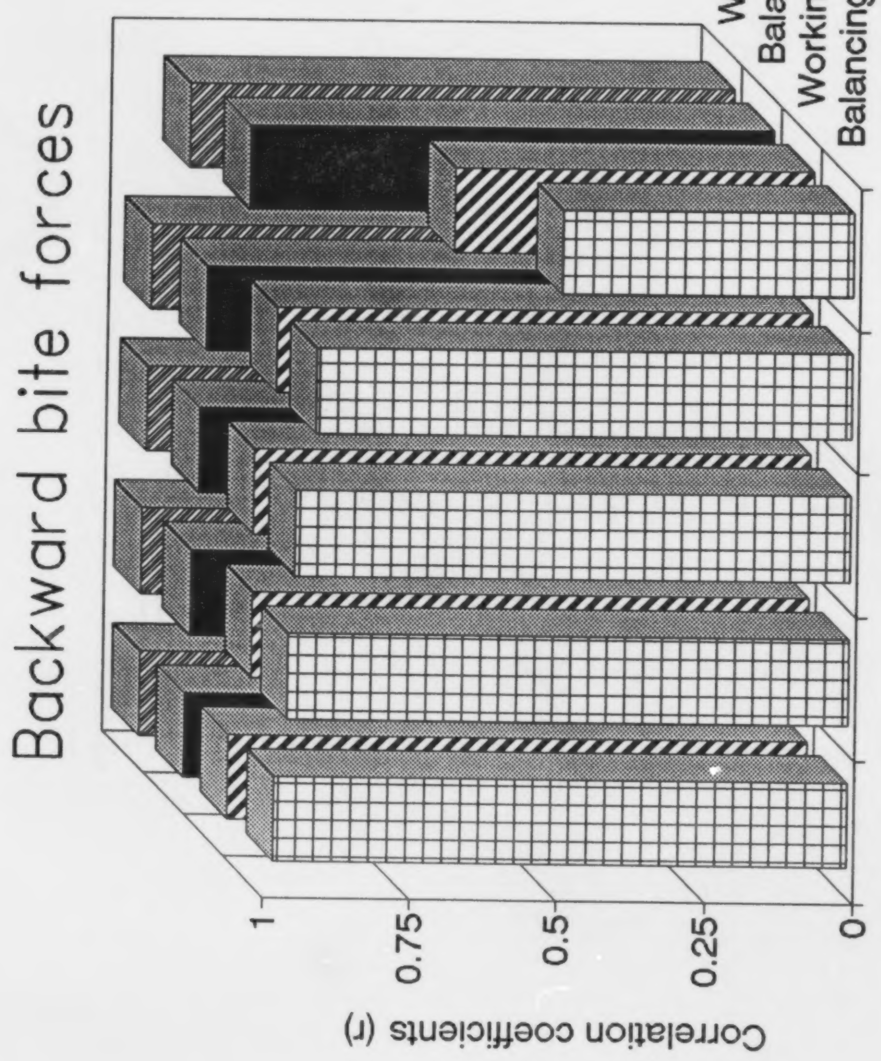

Backward bite forces
Working TM
Balancing TM
Working TM
Balancing MA
Individual bites
Correlation coefficients (r)
1
0.75
0.5
0.25
0

Figure 19

r values for 20° lateral bite forces

TM: temporalis; MA: masseter. All the correlation coefficients (*r* values) were above 0.5 except for the balancing masseter of one subject. This low value was 0.28.

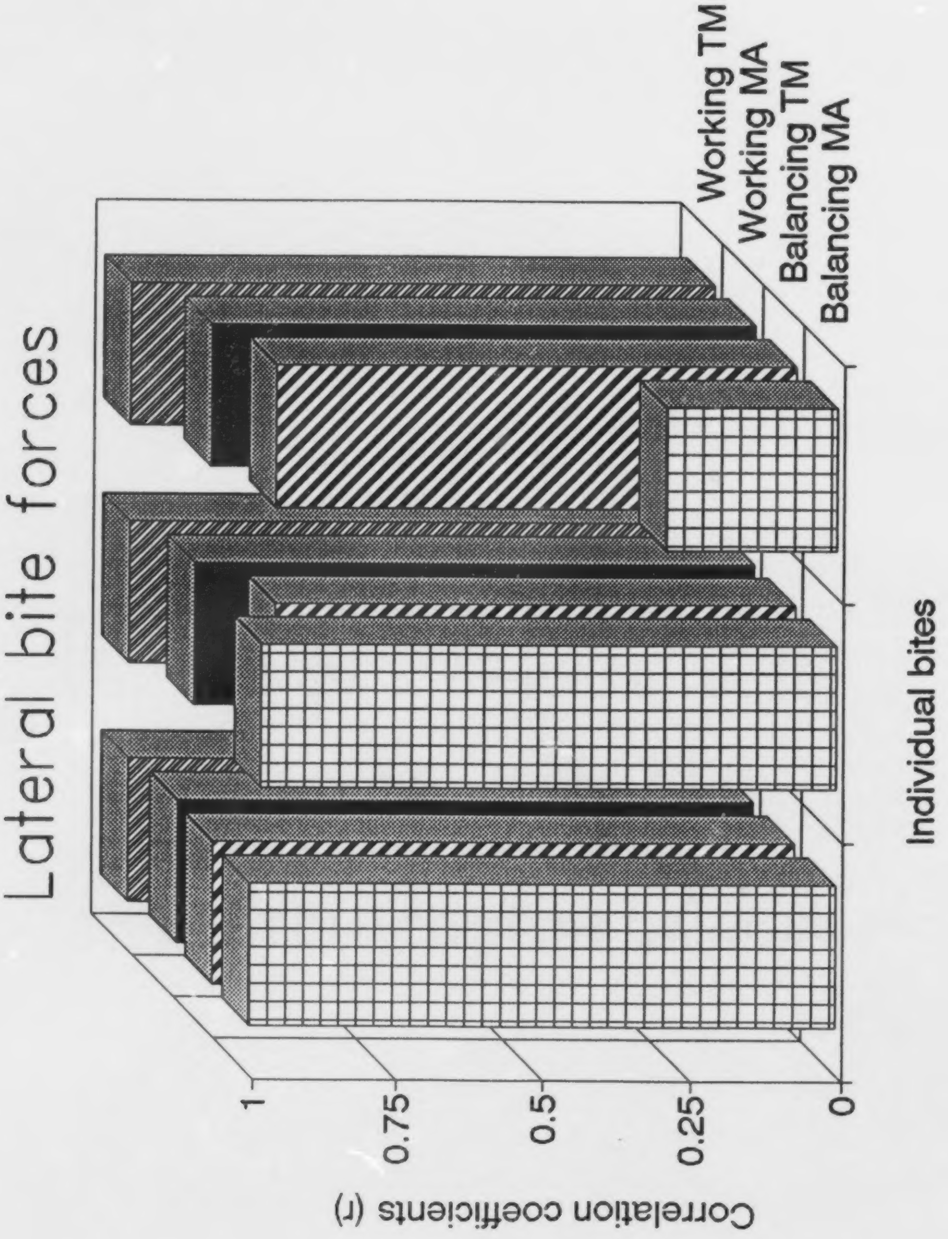

Lateral bite forces
Correlation coefficients (r)
1
0.75
0.5
0.25
0
Individual bites
Working TM
Working MA
Balancing TM
Balancing MA

Figure 20

r values for 20° medial bite forces

TM: temporalis; MA: masseter. Almost all the correlation coefficients (*r* values) were above 0.75.

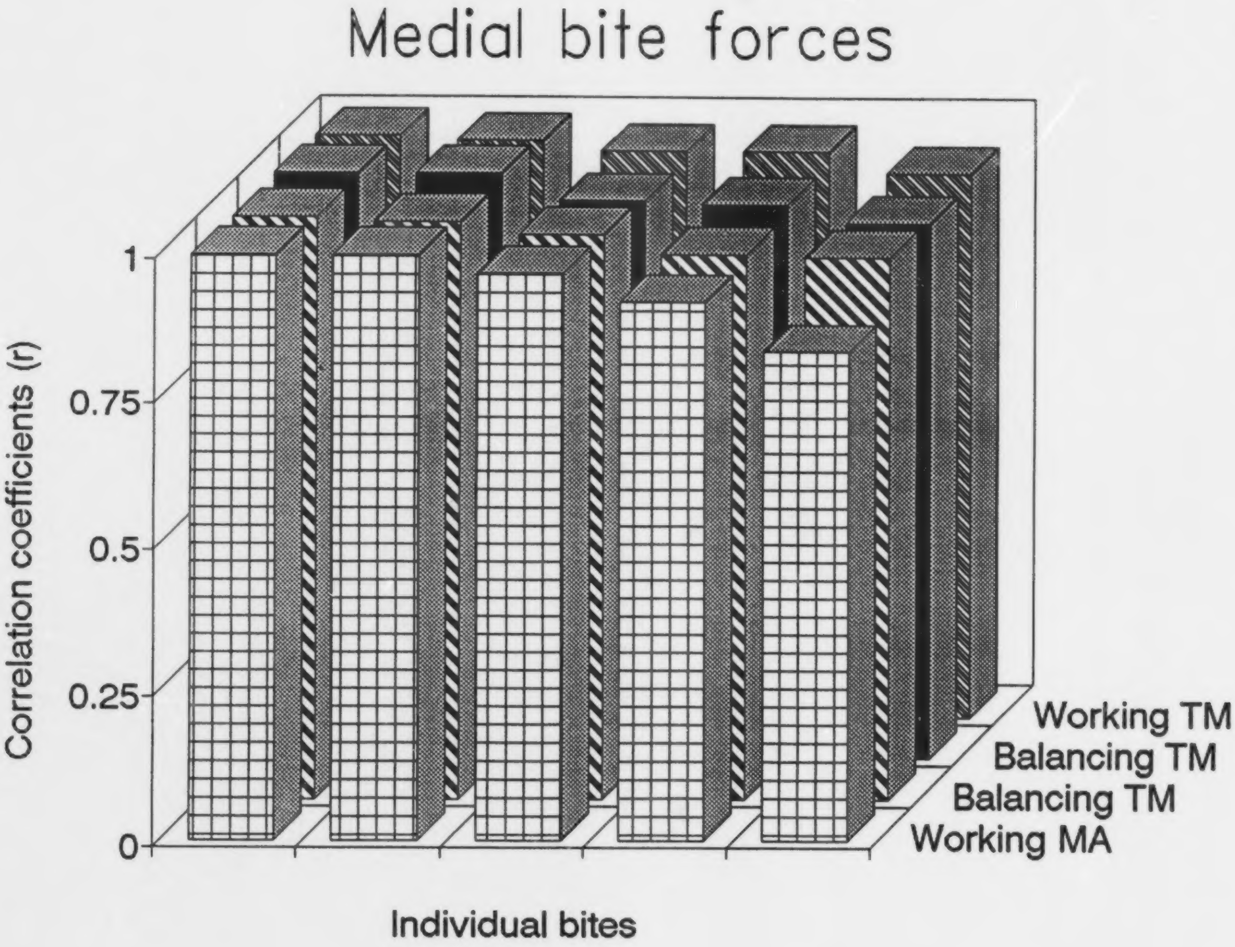

Medial bite forces
Correlation coefficients (r)
1
0.75
0.5
0.25
0
Individual bites
Working TM
Balancing TM
Balancing TM
Working MA

Figure 21

***r* values for vertical bite forces**

TM: temporalis; MA: masseter. Almost all the correlation coefficients (*r* values) were above 0.75 except for the balancing masseter of one subject.

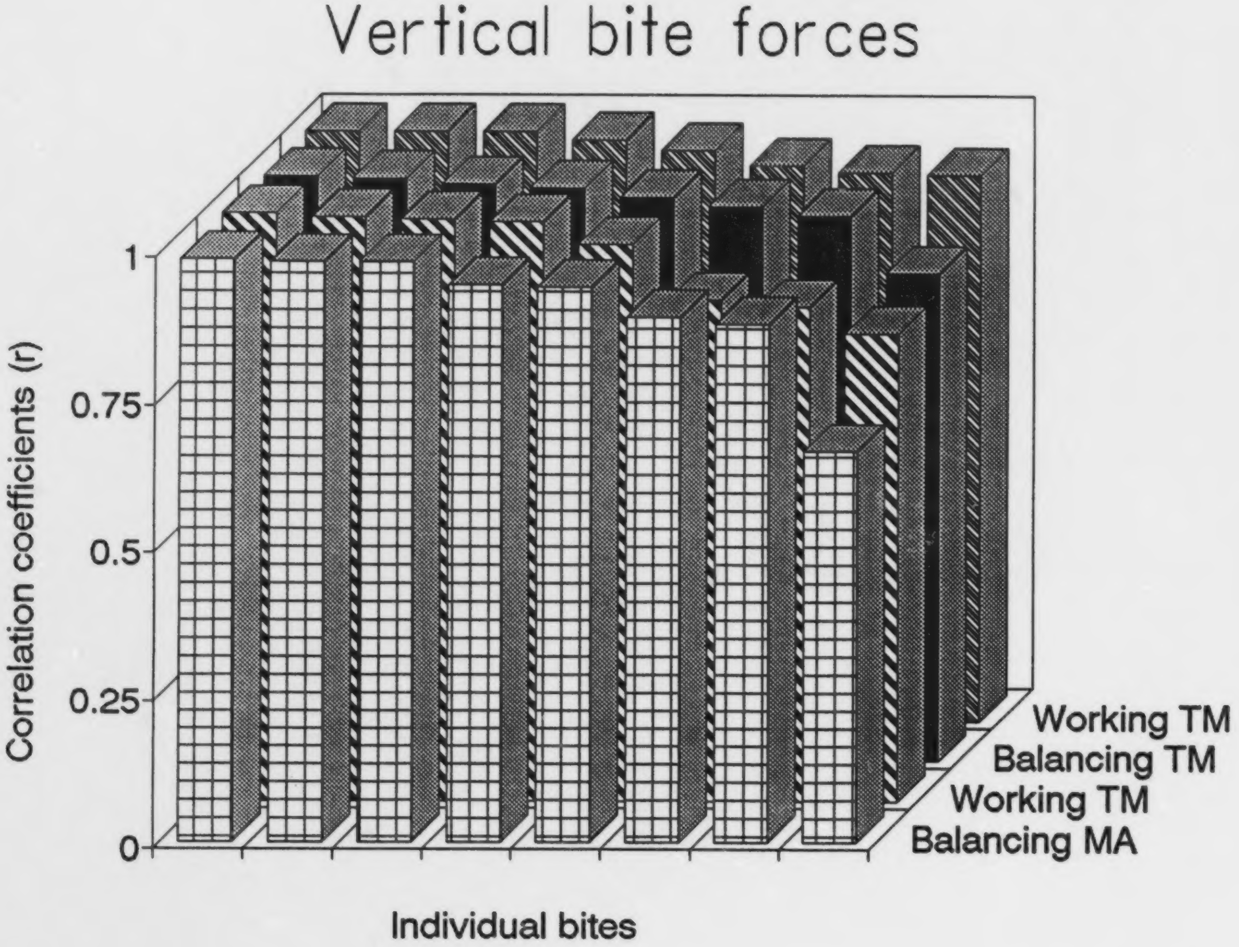

Vertical bite forces
Correlation coefficients (r)
1
0.75
0.5
0.25
0
Individual bites
Working TM
Balancing TM
Working TM
Balancing MA

Figure 22

Mirror image muscle patterns for left and right tasks

There was very good agreement between the regression lines obtained for left and right side experiments when biting parallel to the sagittal plane: the anterior, posterior and vertical bites yielded very good mirror image EMG activities between the left and right muscle patterns. The agreement for medial and lateral bite forces was only moderately good. EMG activities for producing medial bite force showed poor similarities and the sequence of muscle activities was reversed, but all the muscles contracted roughly to the same degree. This was also the situation for vertical bite forces where all the muscles were activated very closely. Note, however, that the sequence of muscle activities for medial and vertical bites were quite different. The left and right muscle patterns for the lateral bites were only marginally good. The working masseter on the left side was more significantly activated as the magnitude of the bite force increased from 100 to 150 *N*. Lateral bite forces yielded the most varied muscle activation patterns between the left and right.

TM: temporalis; MA: masseter.

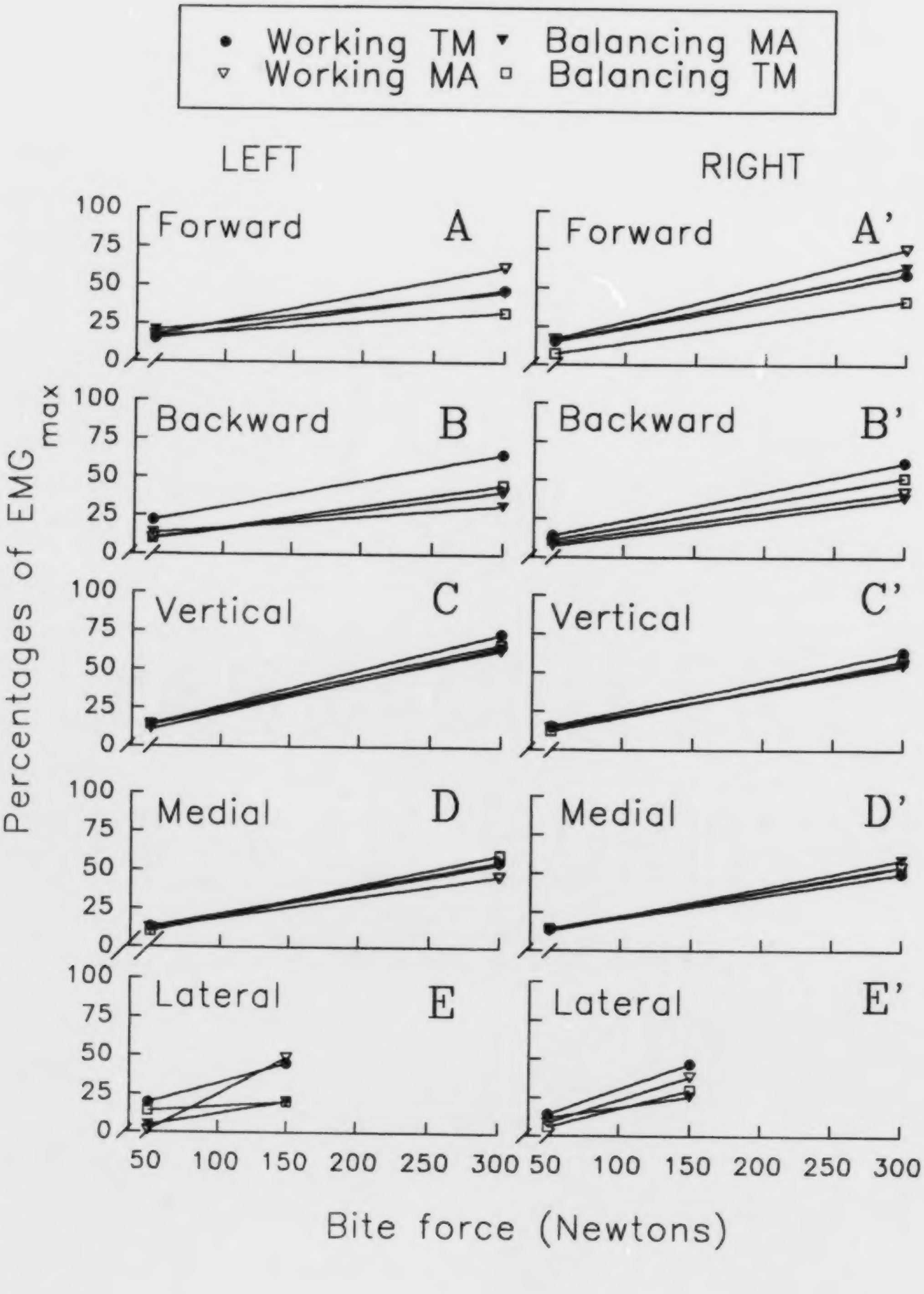

● Working TM
▼ Balancing MA
▽ Working MA
□ Balancing TM
LEFT
RIGHT
Forward
A
Forward
A'
Backward
B
Backward
B'
Vertical
C
Vertical
C'
Medial
D
Medial
D'
Lateral
E
Lateral
E'
0
25
50
75
100
Percentages of EMG$_{max}$
50
100
150
200
250
300
Bite force (Newtons)

Figure 23

The averaged EMG data points for all directions

TM: temporalis; MA: masseter.

A

Working masseter had the greatest activity which reached about 75% of its EMG_{max}. The working temporalis and balancing masseter were equally active and reached about 50% of their respective EMG_{max}. The least activity was found in balancing temporalis and was about 25% of its EMG_{max}.

B

The four muscles were activated to roughly the same degree; all of them reached 60% to 70% of their corresponding EMG_{max}. Working temporalis seemed to have slightly greater activity than the rest. **B'** is identical to B and is for comparison between **D** and **E**.

C

Working temporalis had the greatest activity among all and reached slightly above 60% of its EMG_{max}. Balancing temporalis seemed to have slightly higher activity than the working masseter; both of which reached about 40% to 50% of their EMG_{max}. The least activity was found in balancing masseter which reached about 25% of its EMG_{max}.

D

The four muscles were activated to roughly the same degree; all of them reached 50% to 60% of their corresponding EMG_{max}.

E

Working temporalis had the greatest activity among all and reached slightly above 50% of its EMG_{max}. Working masseter was the second most active muscle and reached about 40% of its EMG_{max}. The balancing masseter and temporalis were the least active muscle both of which reached about 25% of their corresponding EMG_{max}.

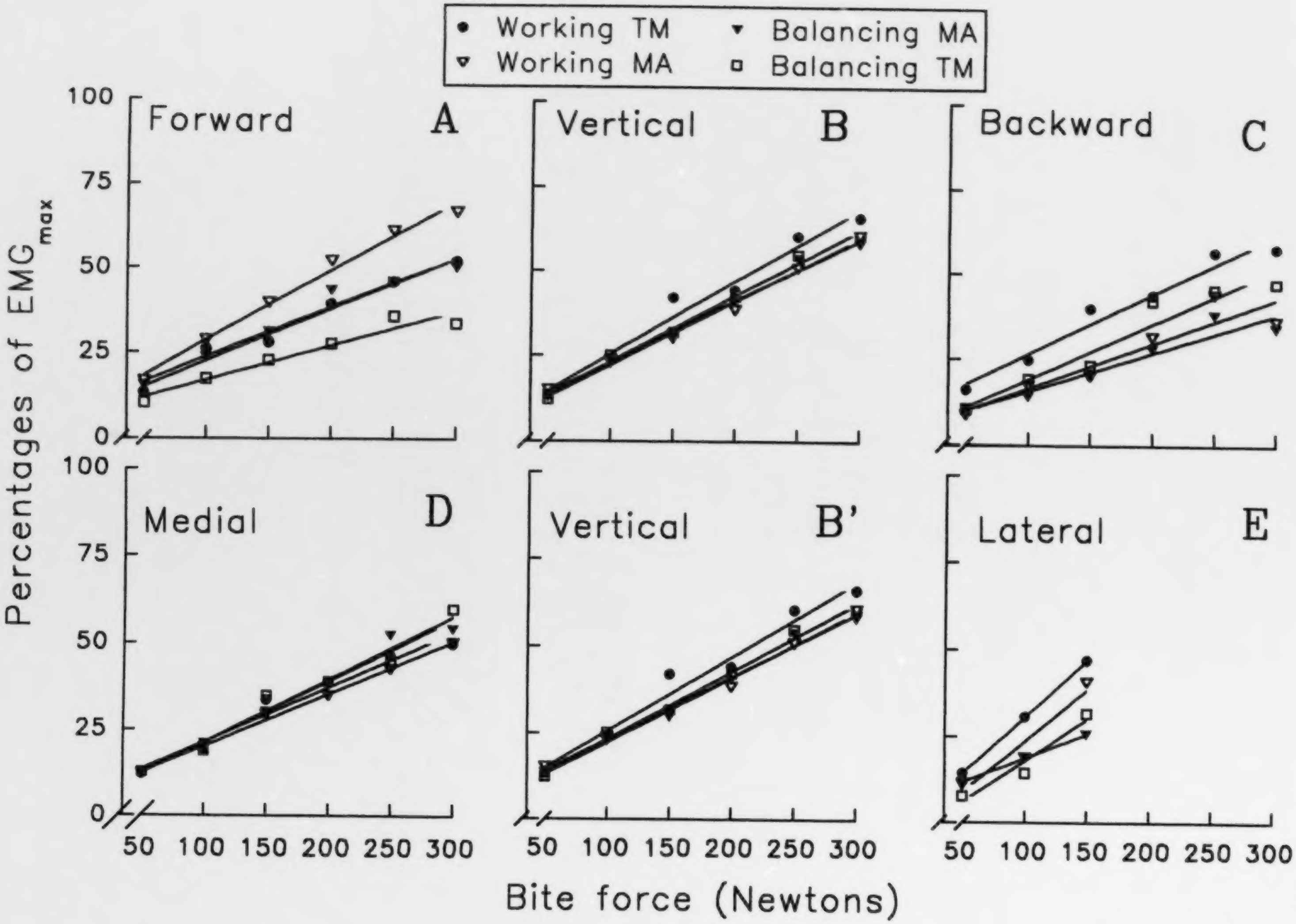

● Working TM
▽ Working MA
▼ Balancing MA
□ Balancing TM
Forward
A
Vertical
B
Backward
C
Medial
D
Vertical
B'
Lateral
E
Percentages of EMG$_{max}$
100
75
50
25
0
50
100
150
200
250
300
Bite force (Newtons)

Figure 24

Sagittal plane: muscle tensions against force directions

The working and balancing temporal muscles had similar activity patterns; note, however, the slopes of the lines for the working side were steeper indicating that working temporalis was more active. Working and balancing masseters showed different patterns: the working being most active for the forward force and the balancing was similarly active for vertical and backward forces.

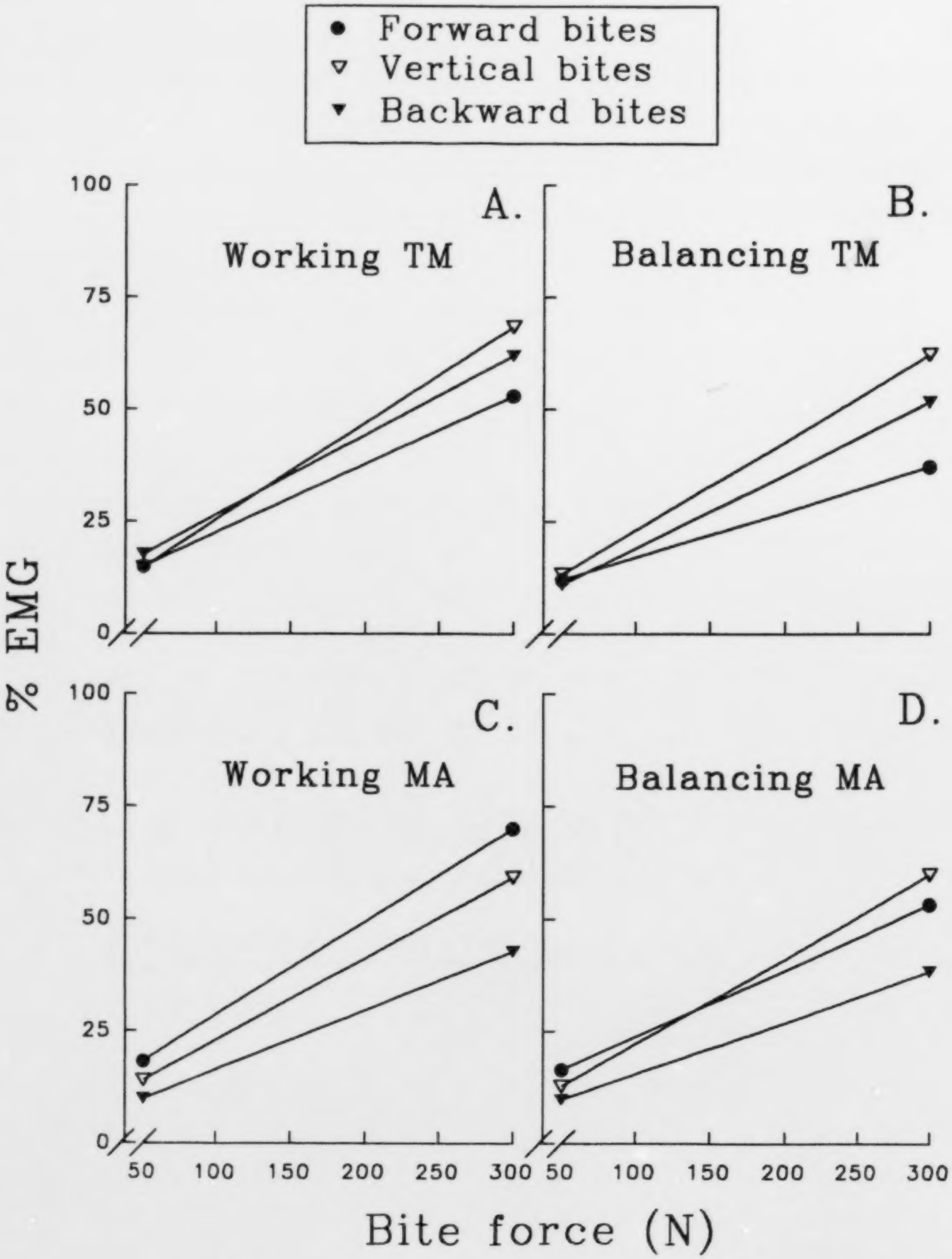

● Forward bites
▽ Vertical bites
▼ Backward bites
A.
Working TM
B.
Balancing TM
C.
Working MA
D.
Balancing MA
% EMG
0
25
50
75
100
50
100
150
200
250
300
Bite force (N)

Figure 25

Frontal plane: muscle tensions against force directions

Vertical bites involved more activity than medial bites in all four muscles. Lateral bites yielded high activities in working side muscles and low activities in the balancing ones.

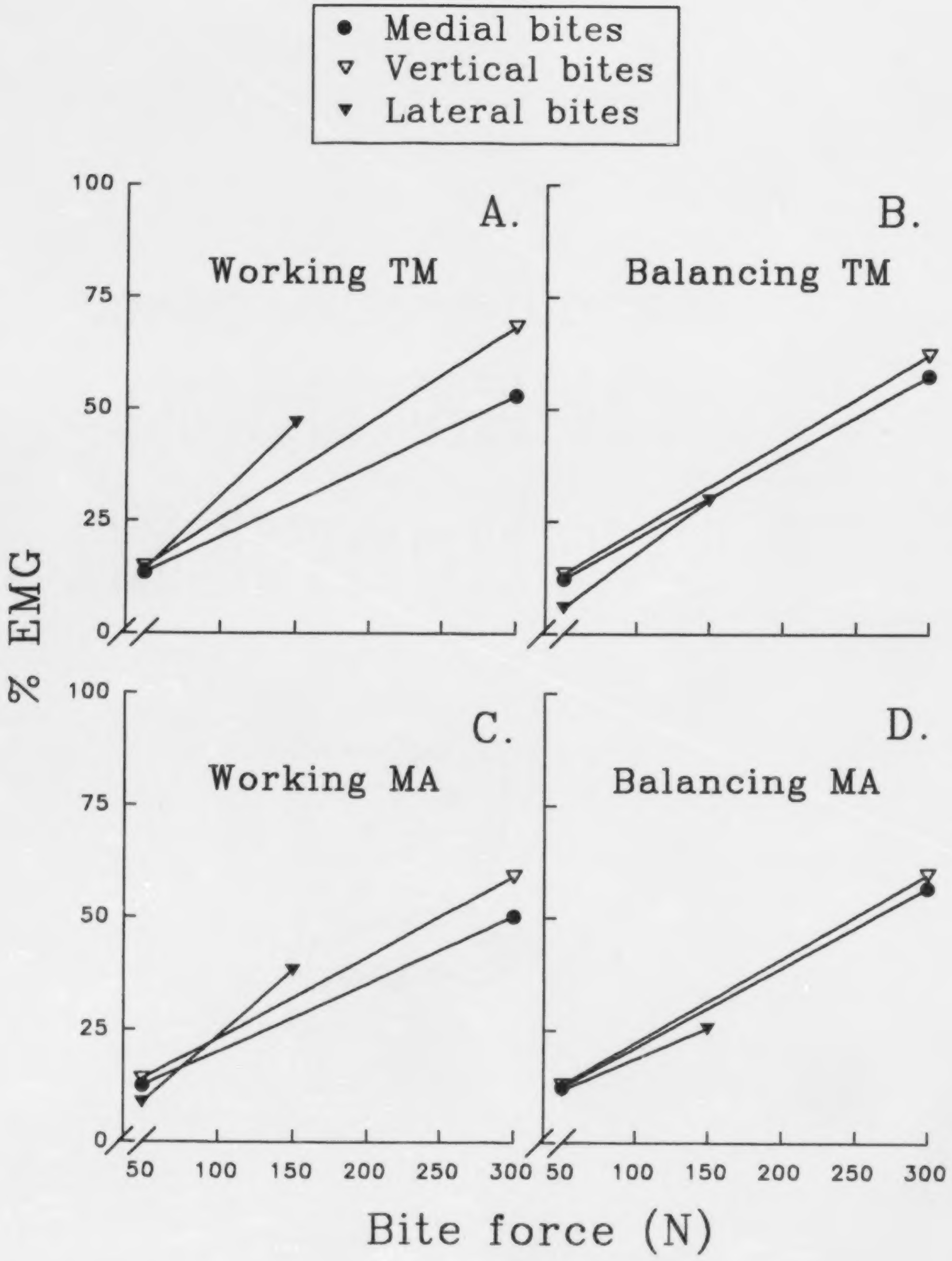

● Medial bites
▽ Vertical bites
▼ Lateral bites
A.
Working TM
B.
Balancing TM
C.
Working MA
D.
Balancing MA
% EMG
0
25
50
75
100
50
100
150
200
250
300
Bite force (N)

Figure 26

Ratios of muscle pairs in the sagittal plane

Comparison of muscles on the same side was more meaningful (than that on both sides): both the ratios of working and balancing pairs were distinctive for any of the three bite force directions.

v.: different from the vertical bite forces.

**: $.05 > p > .01$; ***: $p < .001$.

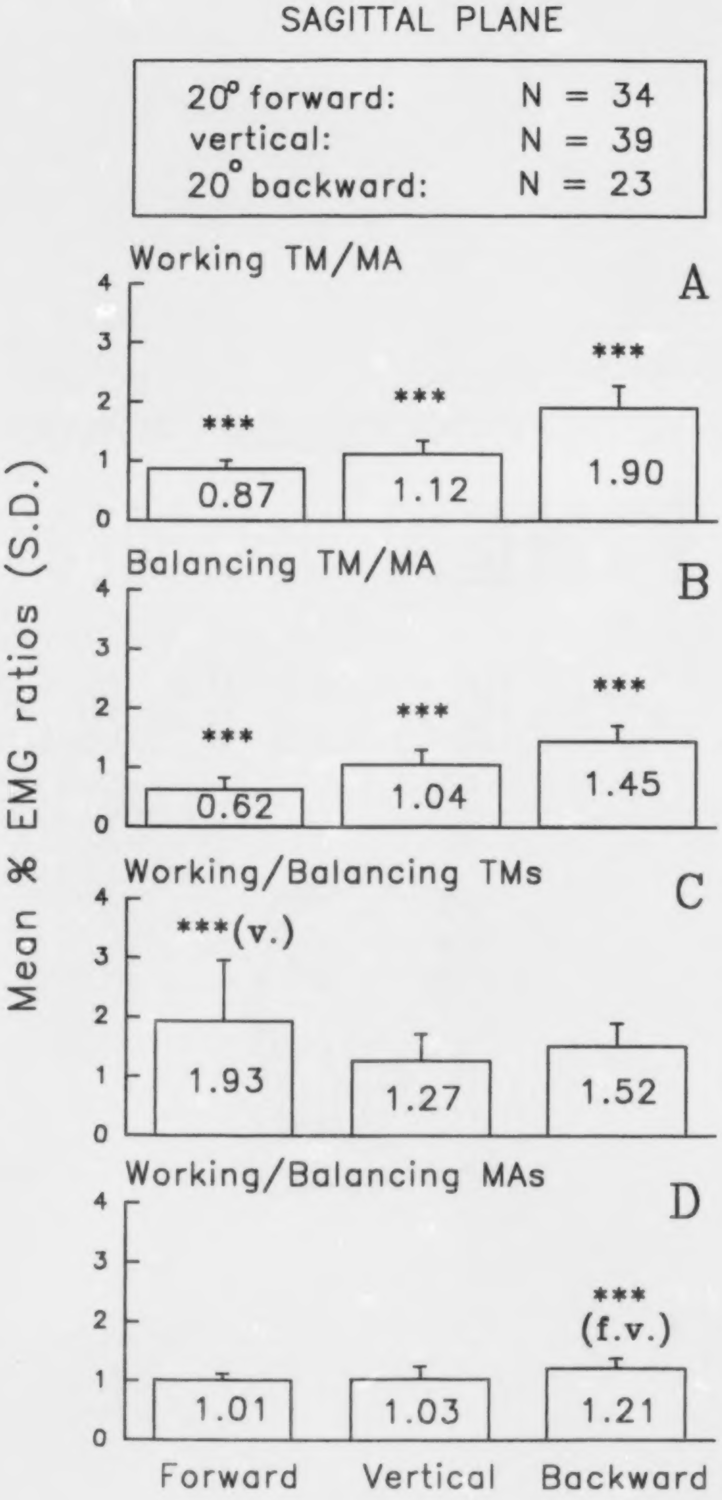

SAGITTAL PLANE
20° forward: N = 34
vertical: N = 39
20° backward: N = 23
Mean % EMG ratios (S.D.)
Working TM/MA
A
0.87
1.12
1.90
***
***
***
Balancing TM/MA
B
0.62
1.04
1.45
***
***
***
Working/Balancing TMs
C
***(v.)
1.93
1.27
1.52
Working/Balancing MAs
D
***
(f.v.)
1.01
1.03
1.21
0
1
2
3
4
Forward
Vertical
Backward

Figure 27

Ratios of muscle pairs in the frontal plane

Both the comparison of muscles on the bilateral sides and on the same side made interesting results. There were always differences in any of the ratios between vertical and 20° lateral bites. Only the ratio of working over balancing temporalis showed significant differences between vertical and 20° medial bites. Even though the plots showing the most and least activated muscles for vertical and medial bite forces were quite different, these ratios failed to show many differences between the two.

m.: different from medial bite forces; **v.**: different from vertical bite forces. **: $.05 > p > .01$; ***: $p < .001$.

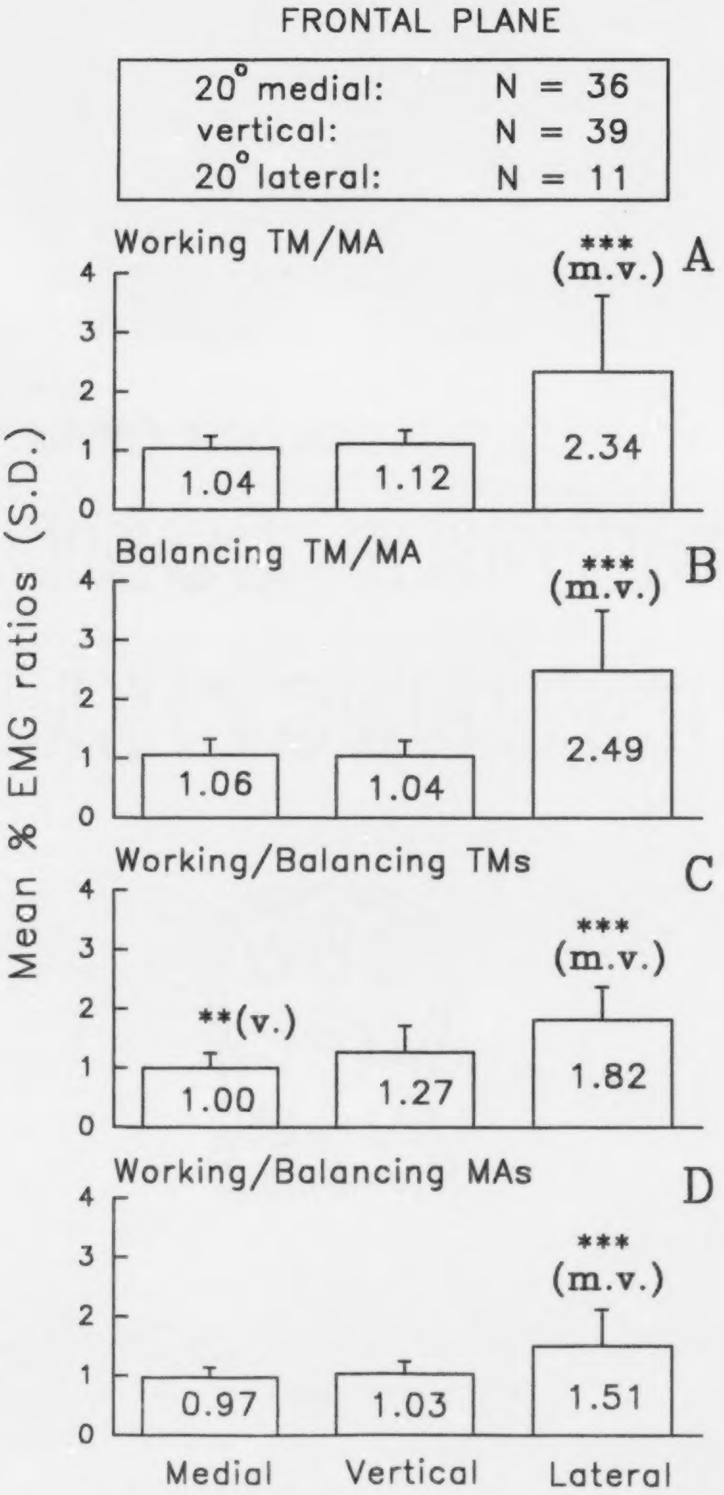
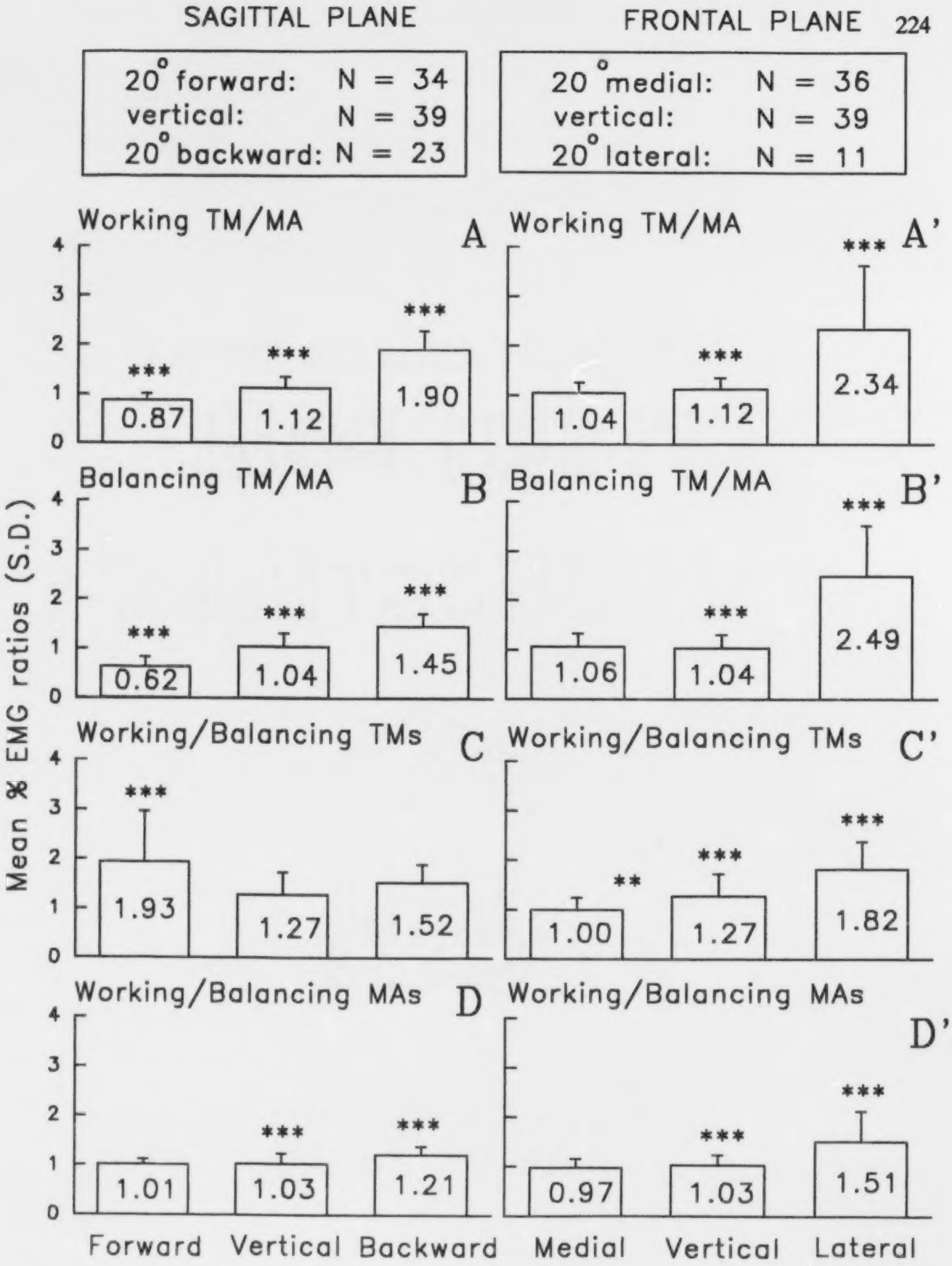

FRONTAL PLANE
20° medial: N = 36
vertical: N = 39
20° lateral: N = 11
Mean % EMG ratios (S.D.)
Working TM/MA
A
***
(m.v.)
1.04
1.12
2.34
Balancing TM/MA
B
***
(m.v.)
1.06
1.04
2.49
Working/Balancing TMs
C
**(v.)
***
(m.v.)
1.00
1.27
1.82
Working/Balancing MAs
D
***
(m.v.)
0.97
1.03
1.51
0
1
2
3
4
Medial
Vertical
Lateral

Figure 28

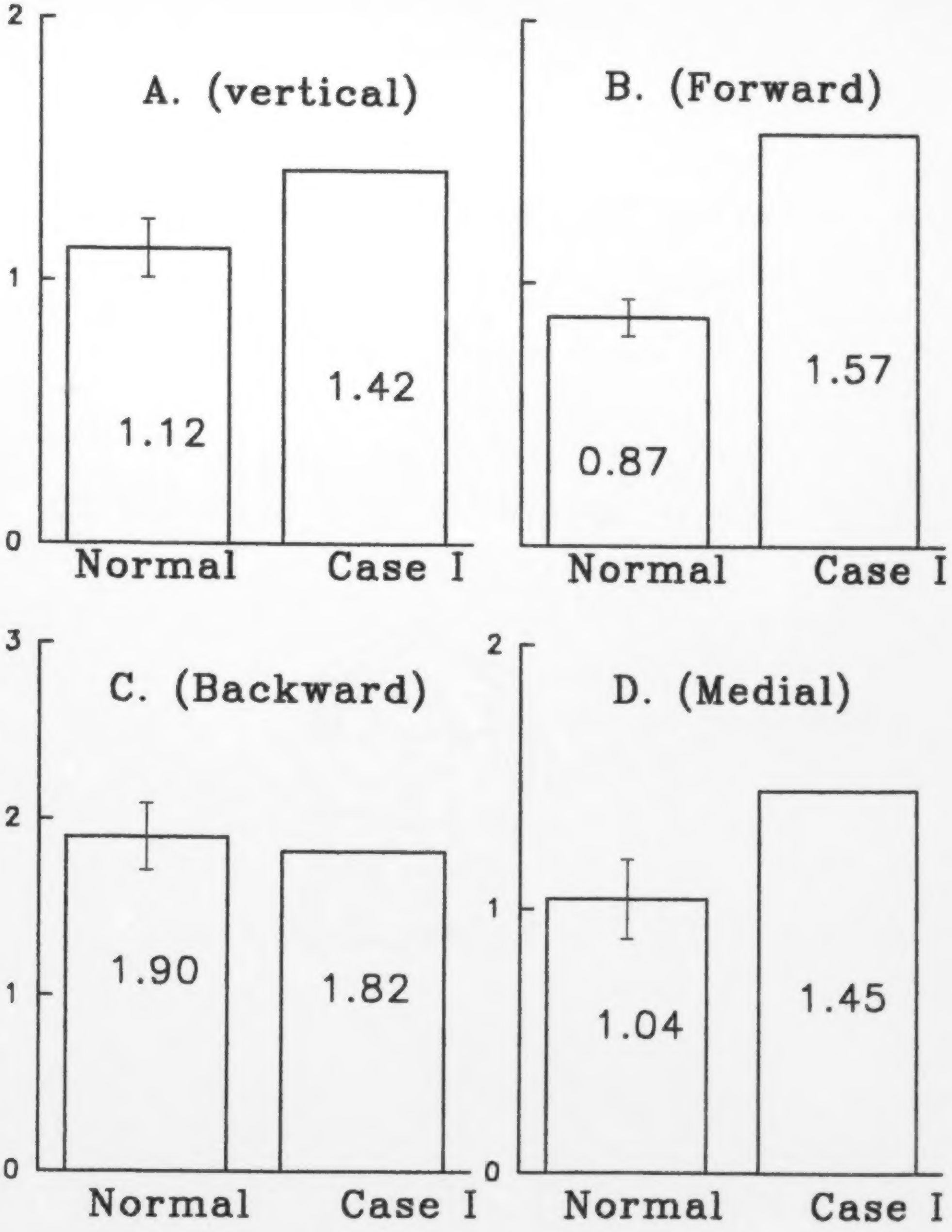
All the ratios in both the sagittal and frontal planes

The following ratios were the most sensitive for all the directions tested: working temporalis over working masseter (28A), balancing temporalis over balancing masseter (28B), and working over balancing temporal muscles (28C'). Ratios showing differences of 2 out of 3 directions in a group included (1) working temporalis over working masseter (28A'); (2) balancing temporalis over balancing masseter (28B'); (3) working over balancing masseters (28D); and working over balancing masseters (28D'). The ratio of working over balancing temporalis in the sagittal plane only showed difference between one two directions.

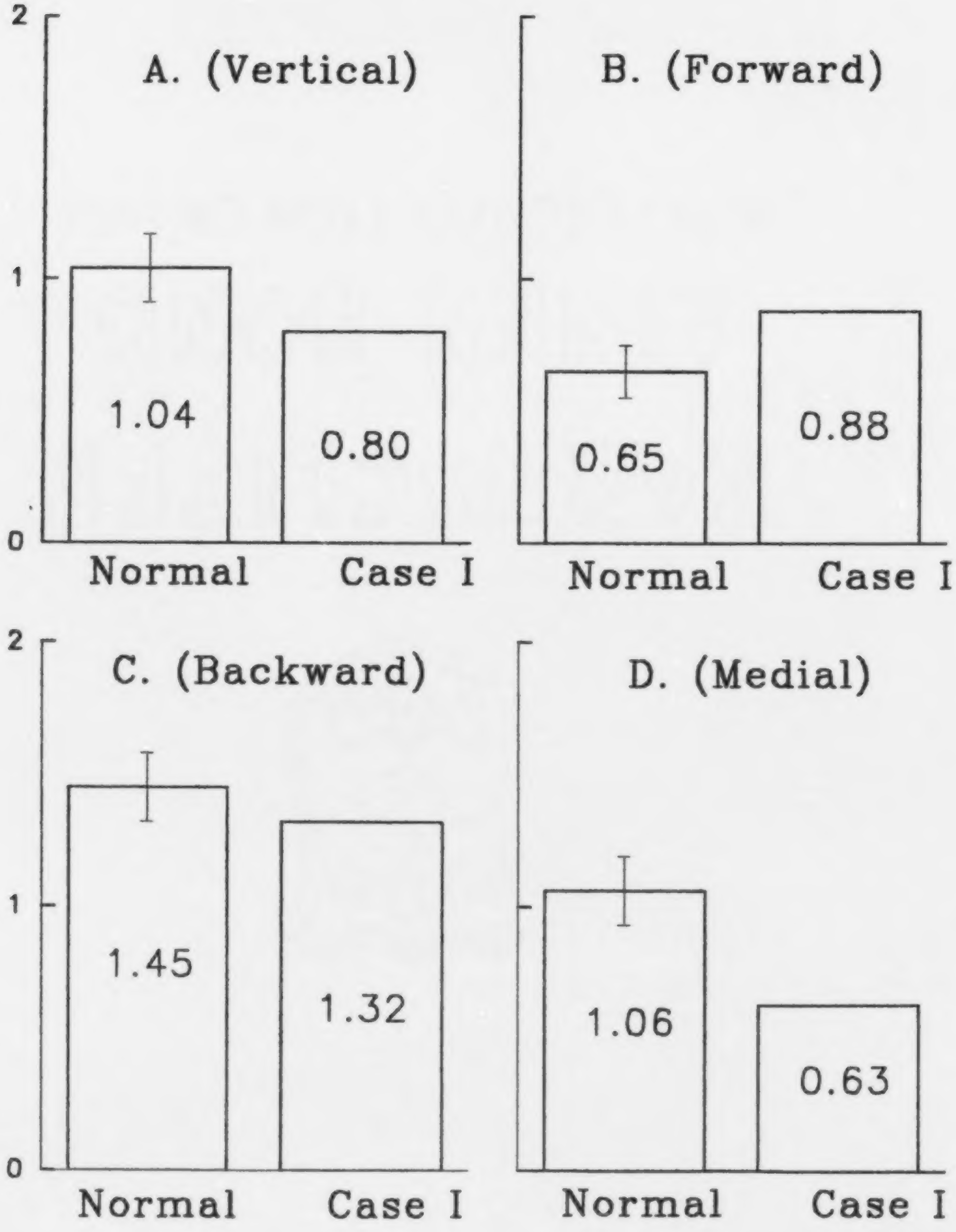
**: $.05 > p > .01$; ***: $p < .001$.

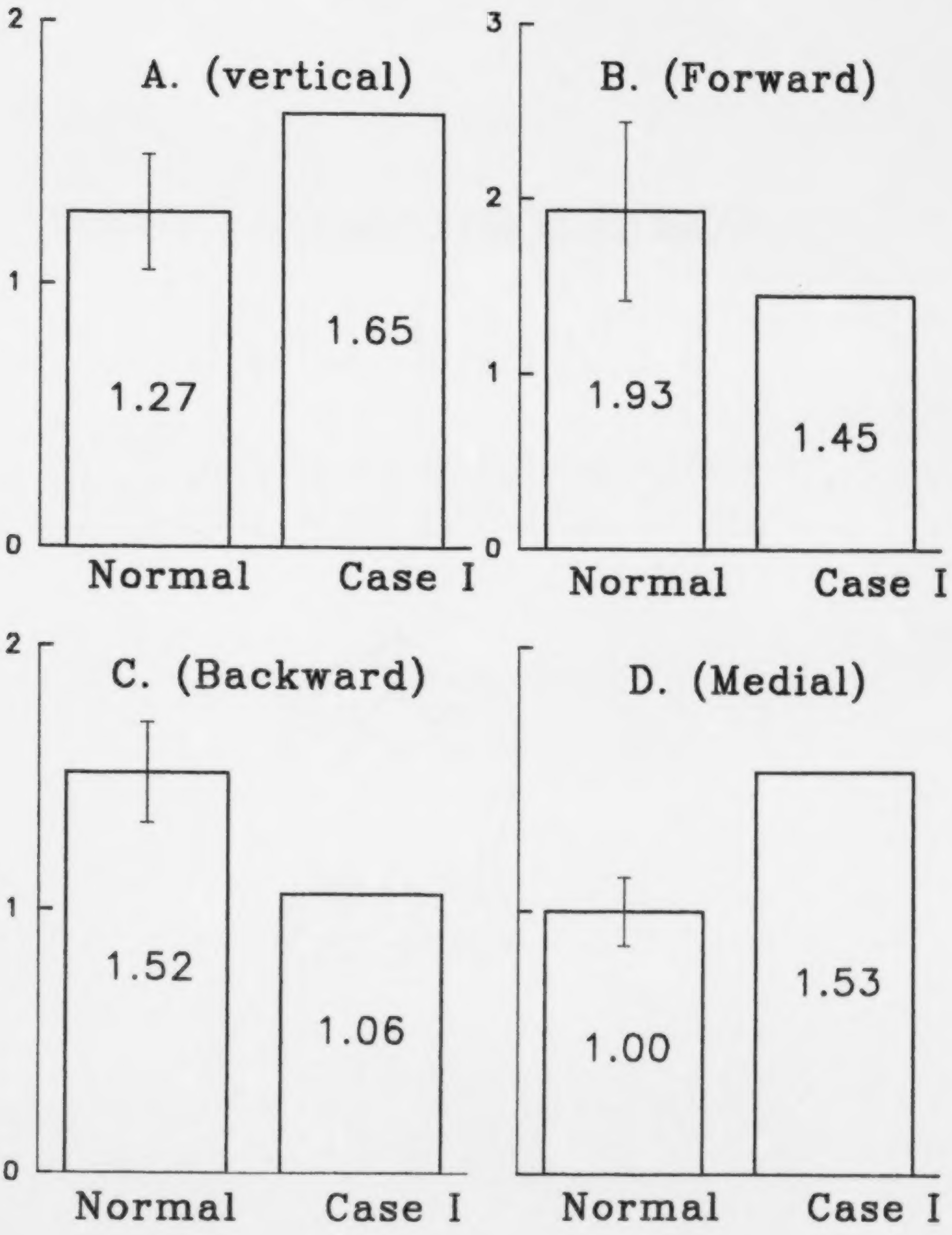

SAGITTAL PLANE
20° forward: N = 34
vertical: N = 39
20° backward: N = 23
FRONTAL PLANE
20° medial: N = 36
vertical: N = 39
20° lateral: N = 11
Mean % EMG ratios (S.D.)
Working TM/MA
A
***
0.87
***
1.12
***
1.90
Working TM/MA
A'
1.04
***
1.12
***
2.34
Balancing TM/MA
B
***
0.62
***
1.04
***
1.45
Balancing TM/MA
B'
1.06
***
1.04
***
2.49
Working/Balancing TMs
C
***
1.93
1.27
1.52
Working/Balancing TMs
C'
**
1.00
***
1.27
***
1.82
Working/Balancing MAs
D
1.01
***
1.03
***
1.21
Working/Balancing MAs
D'
0.97
***
1.03
***
1.51
0
1
2
3
4
Forward
Vertical
Backward
Medial
Vertical
Lateral

Working TM/MA



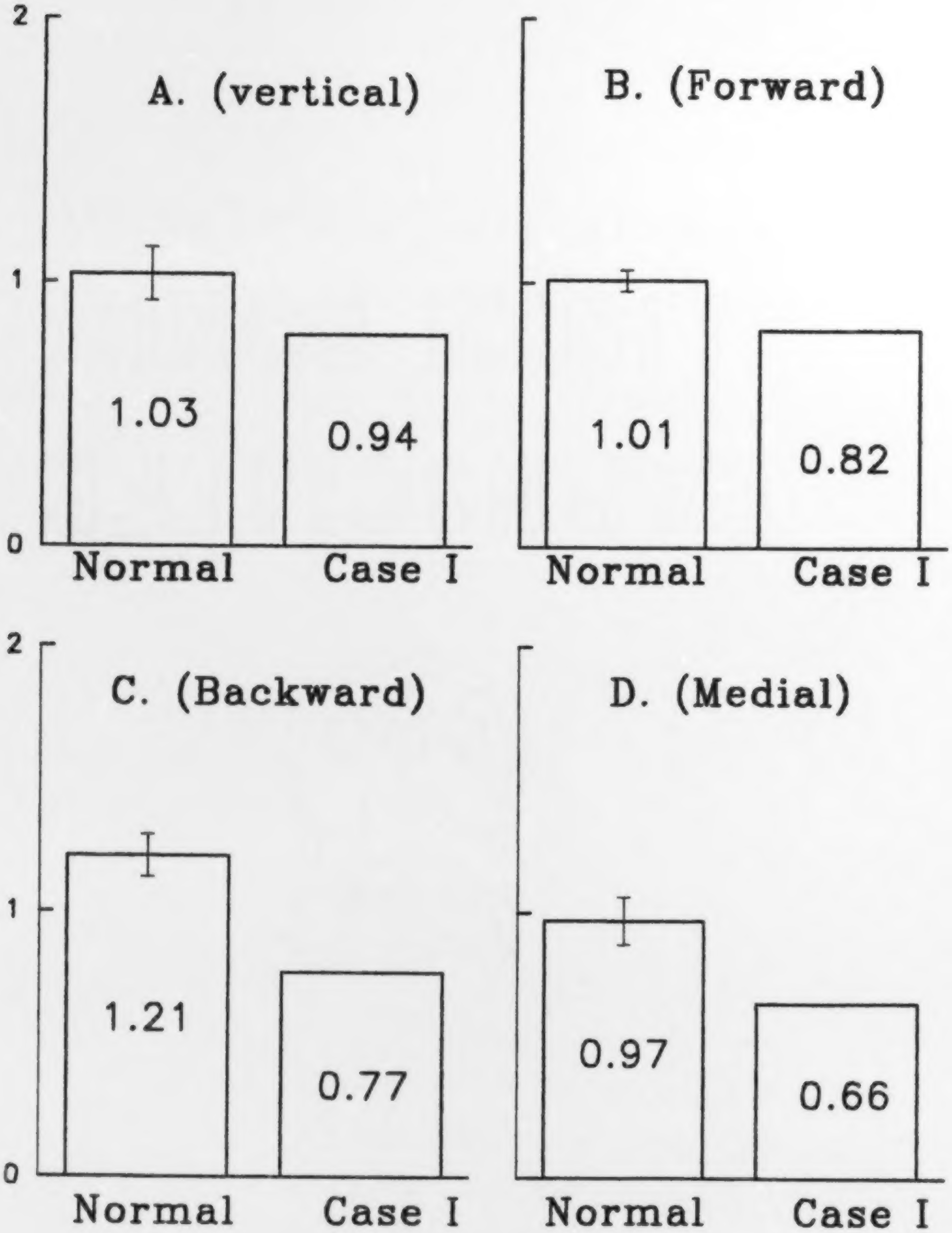
Balancing TM/MA

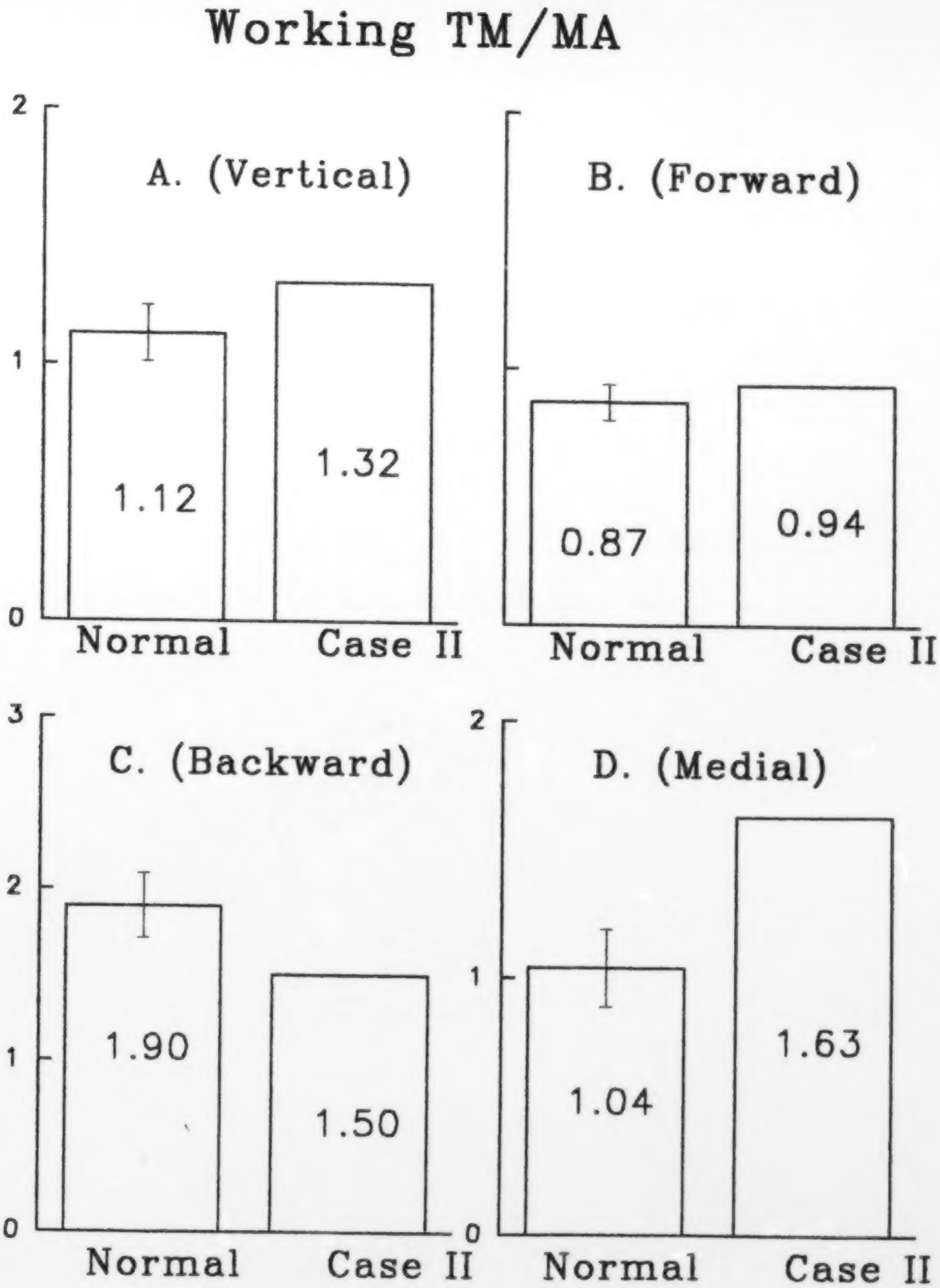


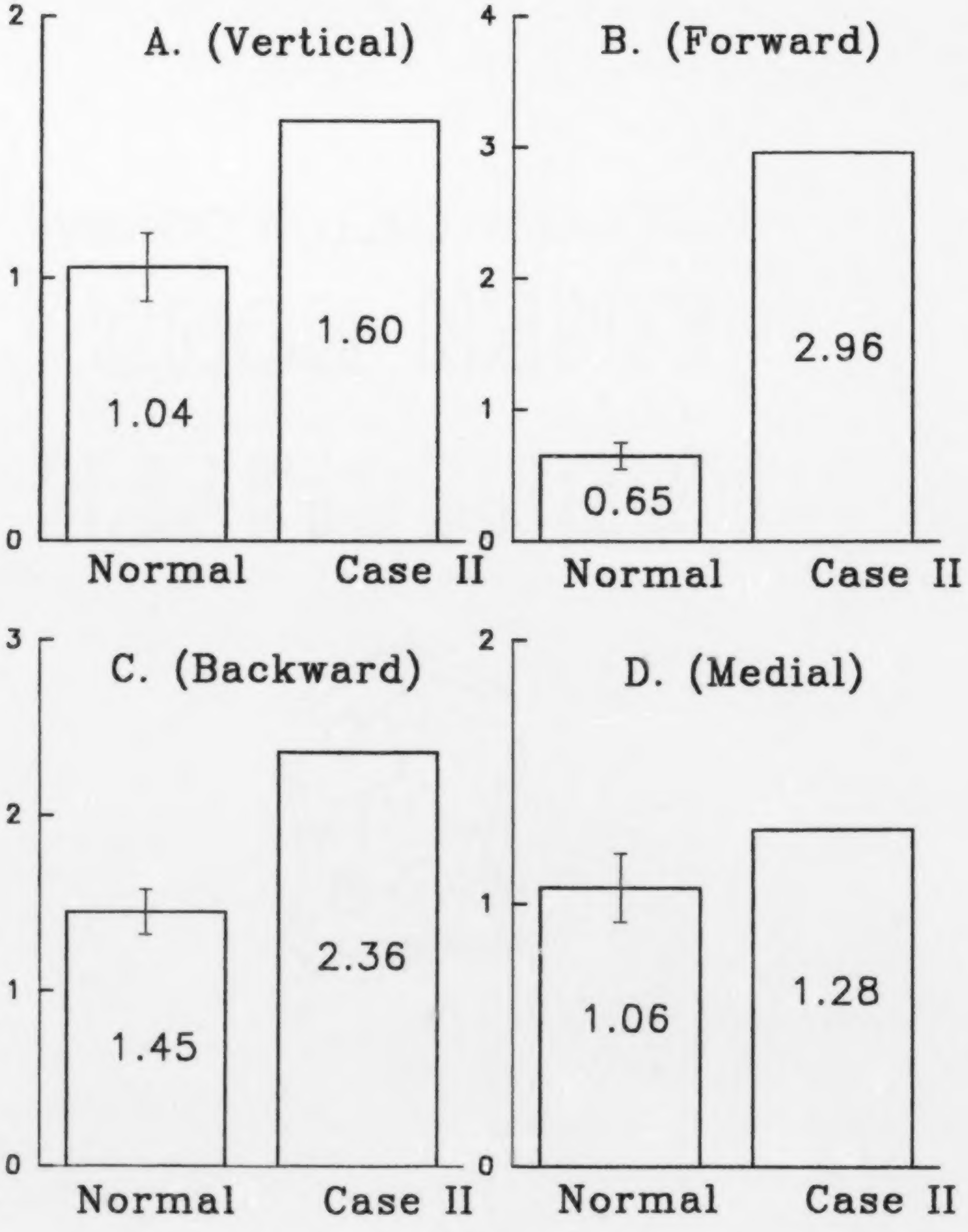


Working/balancing TMs

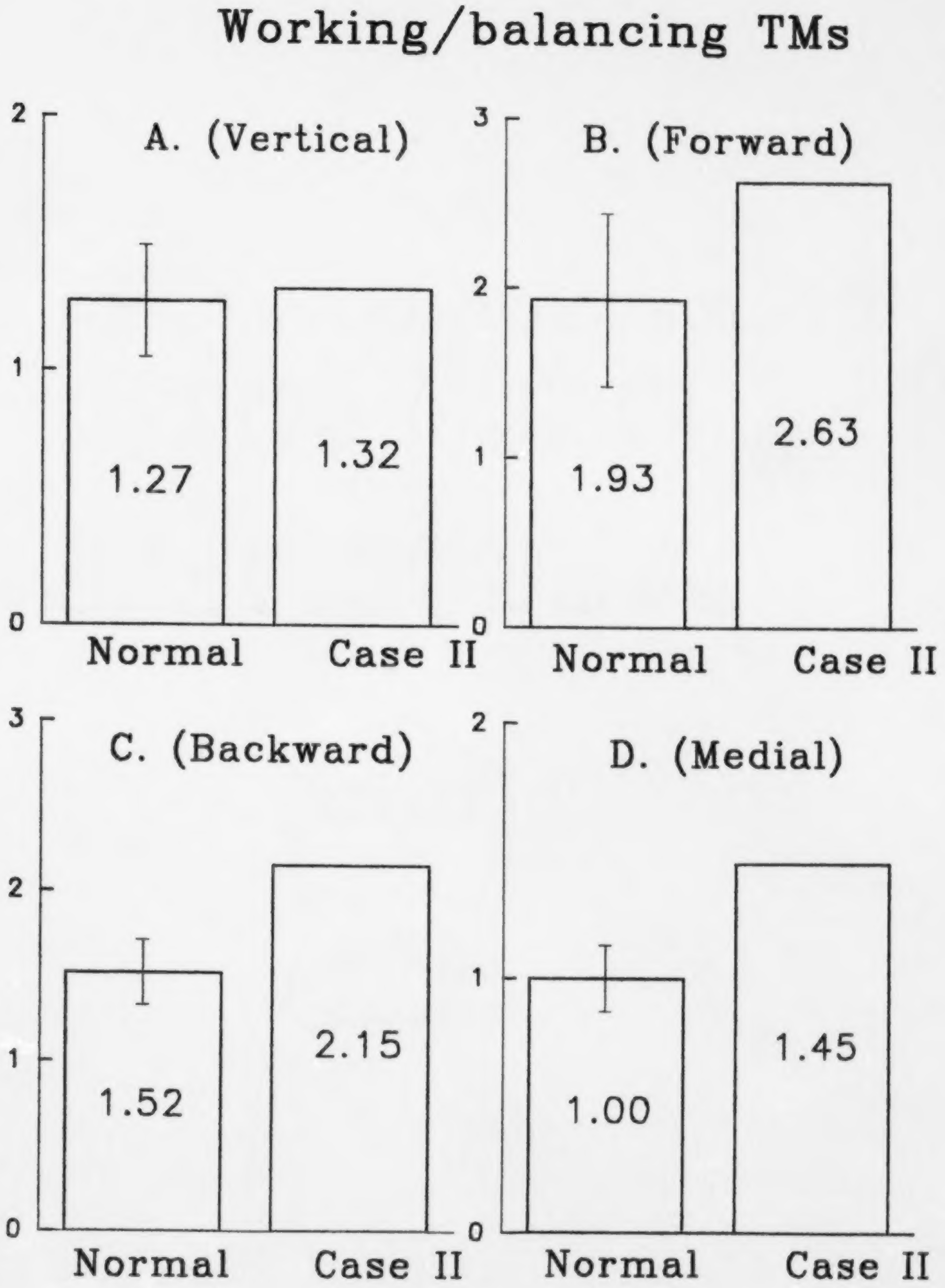
Working/Balancing MAs

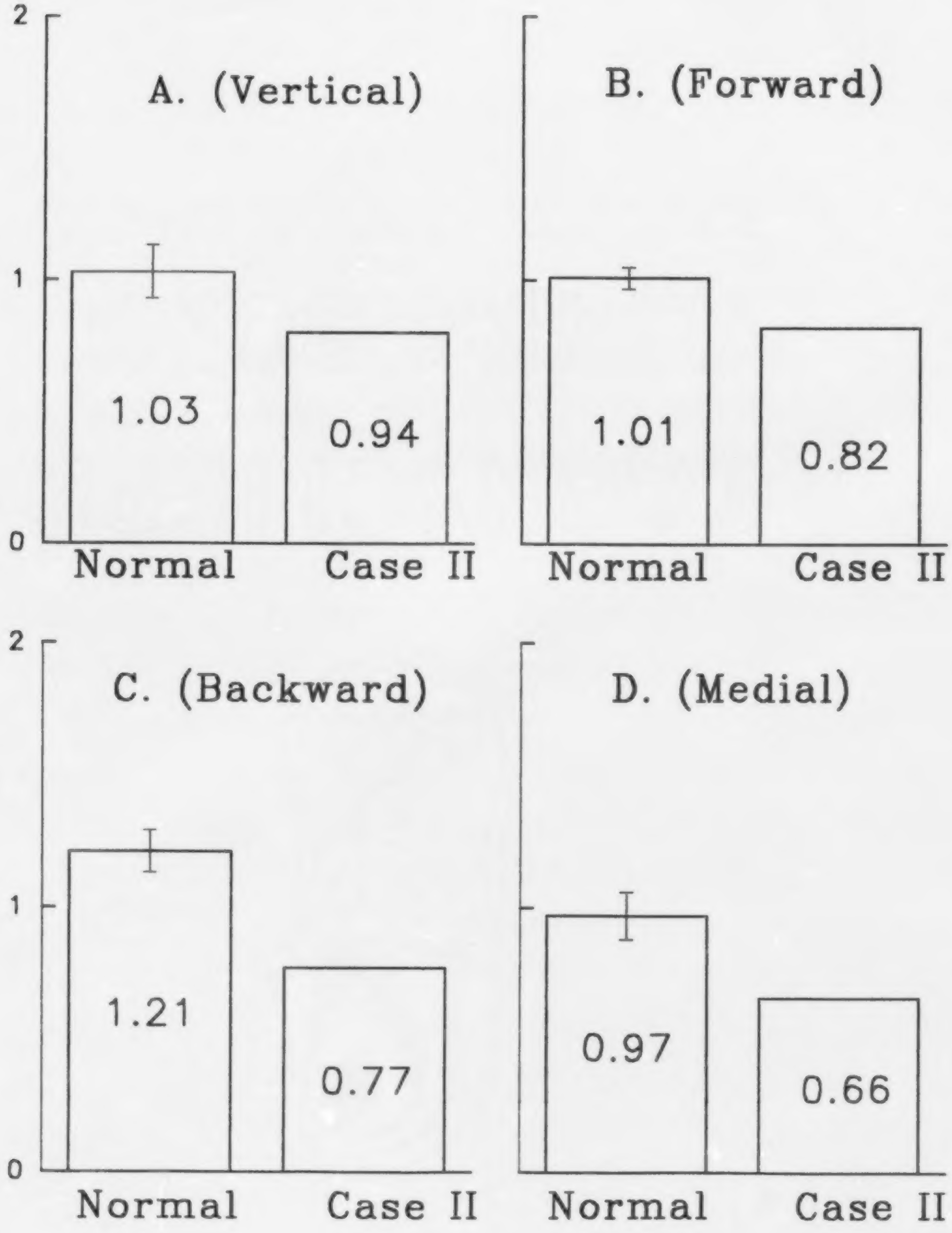



Working TM/MA
A. (Vertical)
2
1
0
1.12
1.32
Normal
Case II
B. (Forward)
0.87
0.94
Normal
Case II
C. (Backward)
3
2
1
0
1.90
1.50
Normal
Case II
D. (Medial)
2
1
0
1.04
1.63
Normal
Case II



Balancing TM/MA


Working/balancing TMs
A. (Vertical)
2
1
0
1.27
1.32
Normal
Case II
B. (Forward)
3
2
1
0
1.93
2.63
Normal
Case II
C. (Backward)
3
2
1
0
1.52
2.15
Normal
Case II
D. (Medial)
2
1
0
1.00
1.45
Normal
Case II



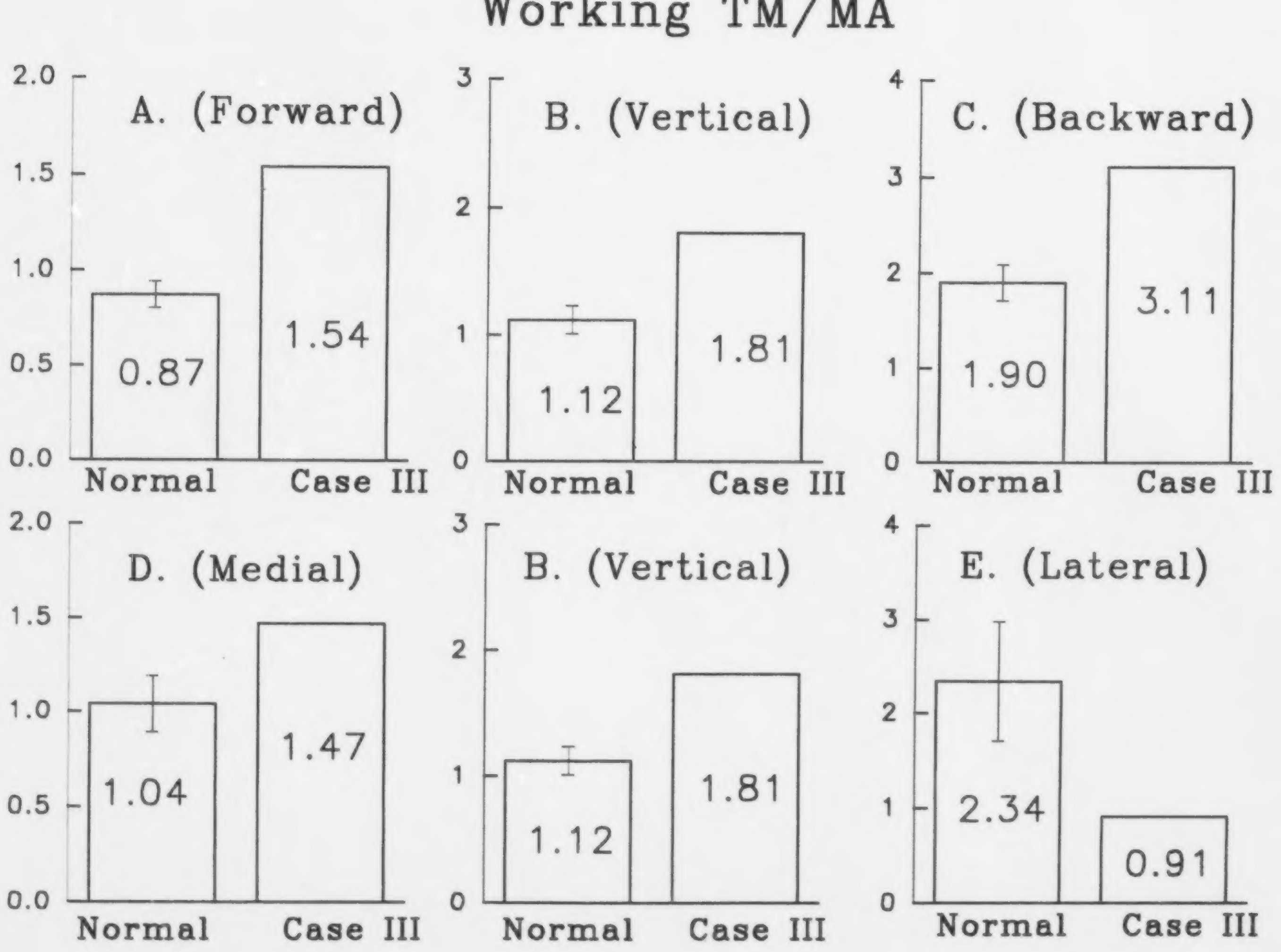
Working/balancing MAs

A. (Vertical)

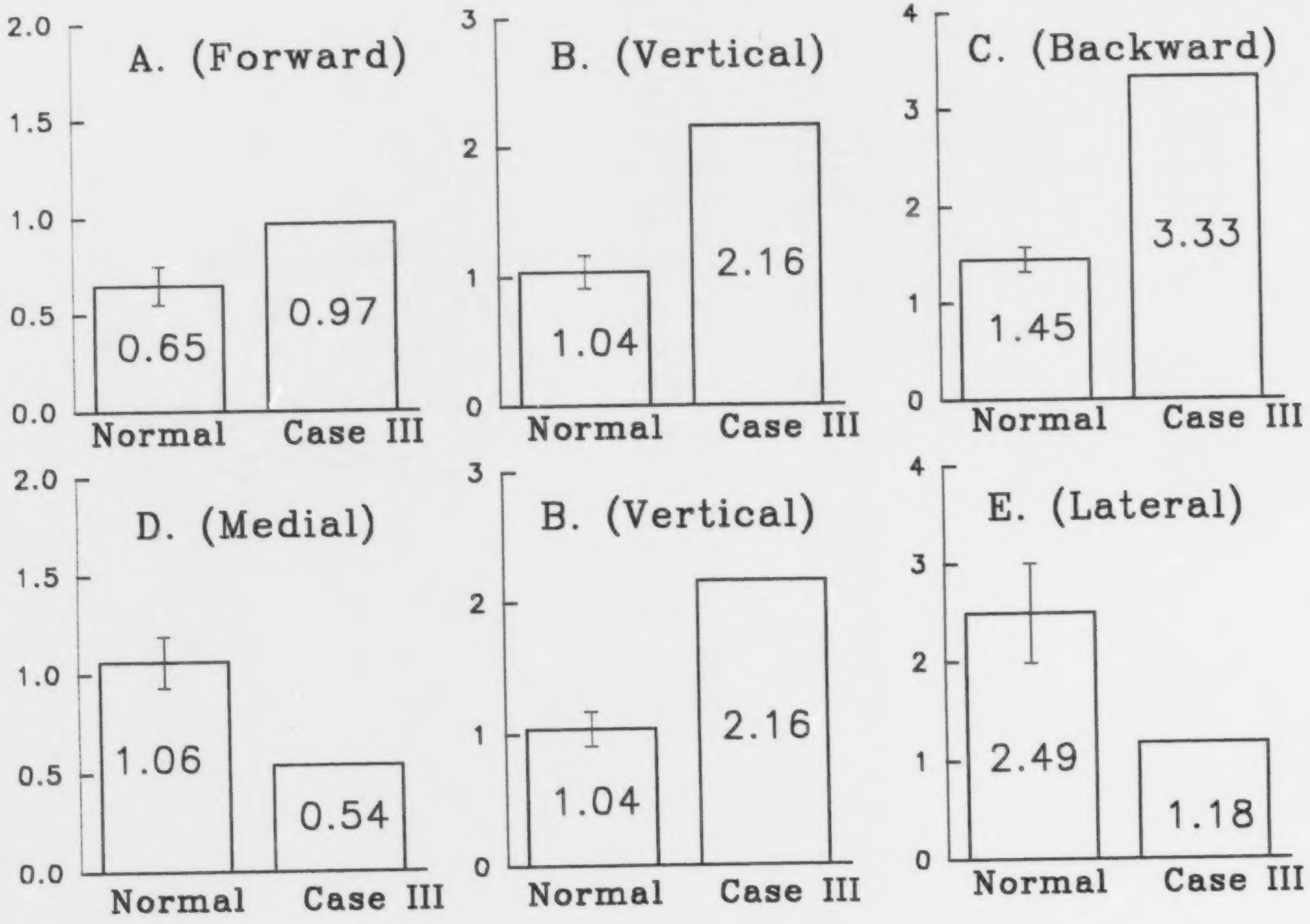
B. (Forward)

C. (Backward)

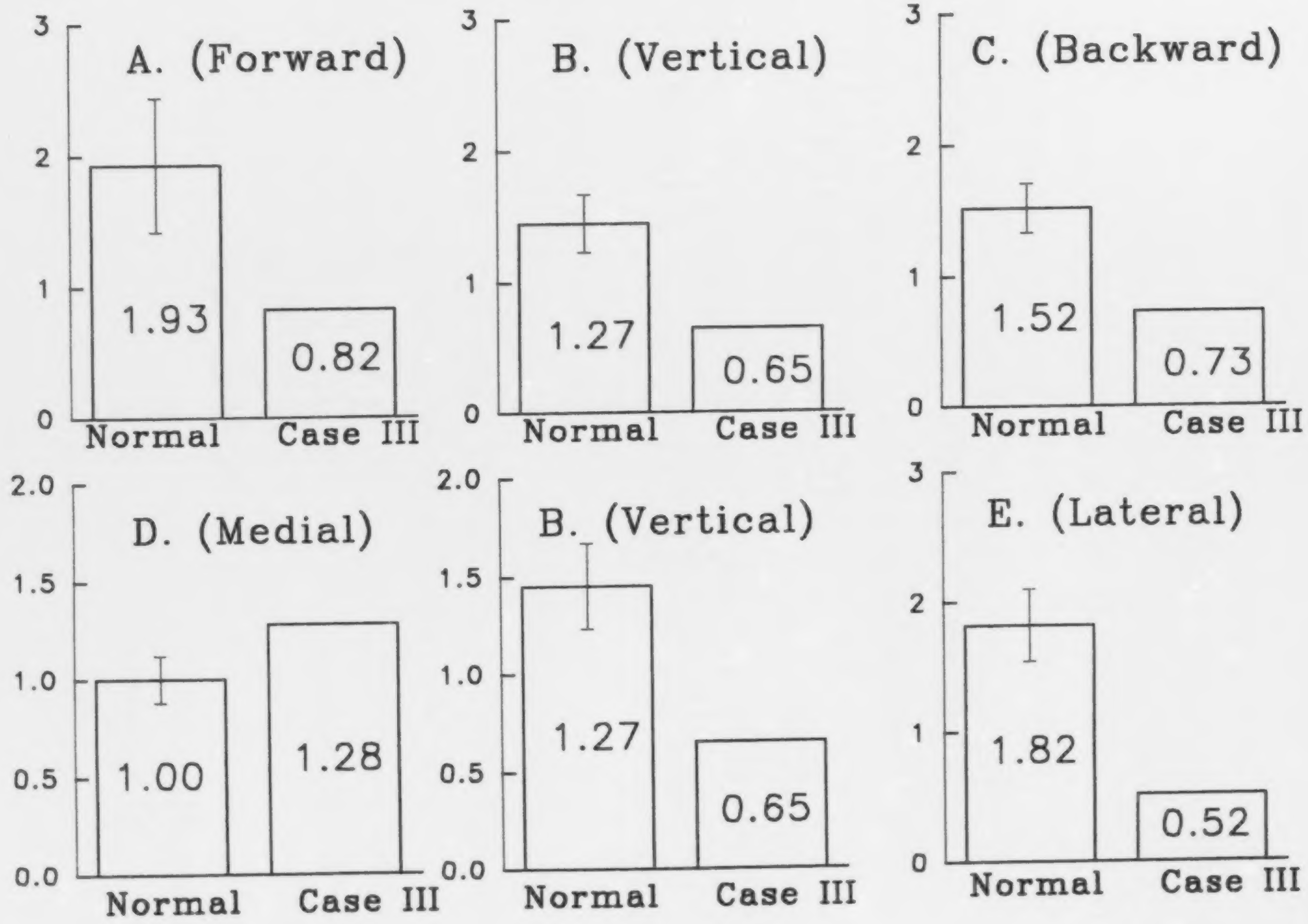
D. (Medial)


Working TM/MA
A. (Forward)
2.0
1.5
1.0
0.5
0.0
0.87
1.54
Normal
Case III
B. (Vertical)
3
2
1
0
1.12
1.81
Normal
Case III
C. (Backward)
4
3
2
1
0
1.90
3.11
Normal
Case III
D. (Medial)
2.0
1.5
1.0
0.5
0.0
1.04
1.47
Normal
Case III
B. (Vertical)
3
2
1
0
1.12
1.81
Normal
Case III
E. (Lateral)
4
3
2
1
0
2.34
0.91
Normal
Case III

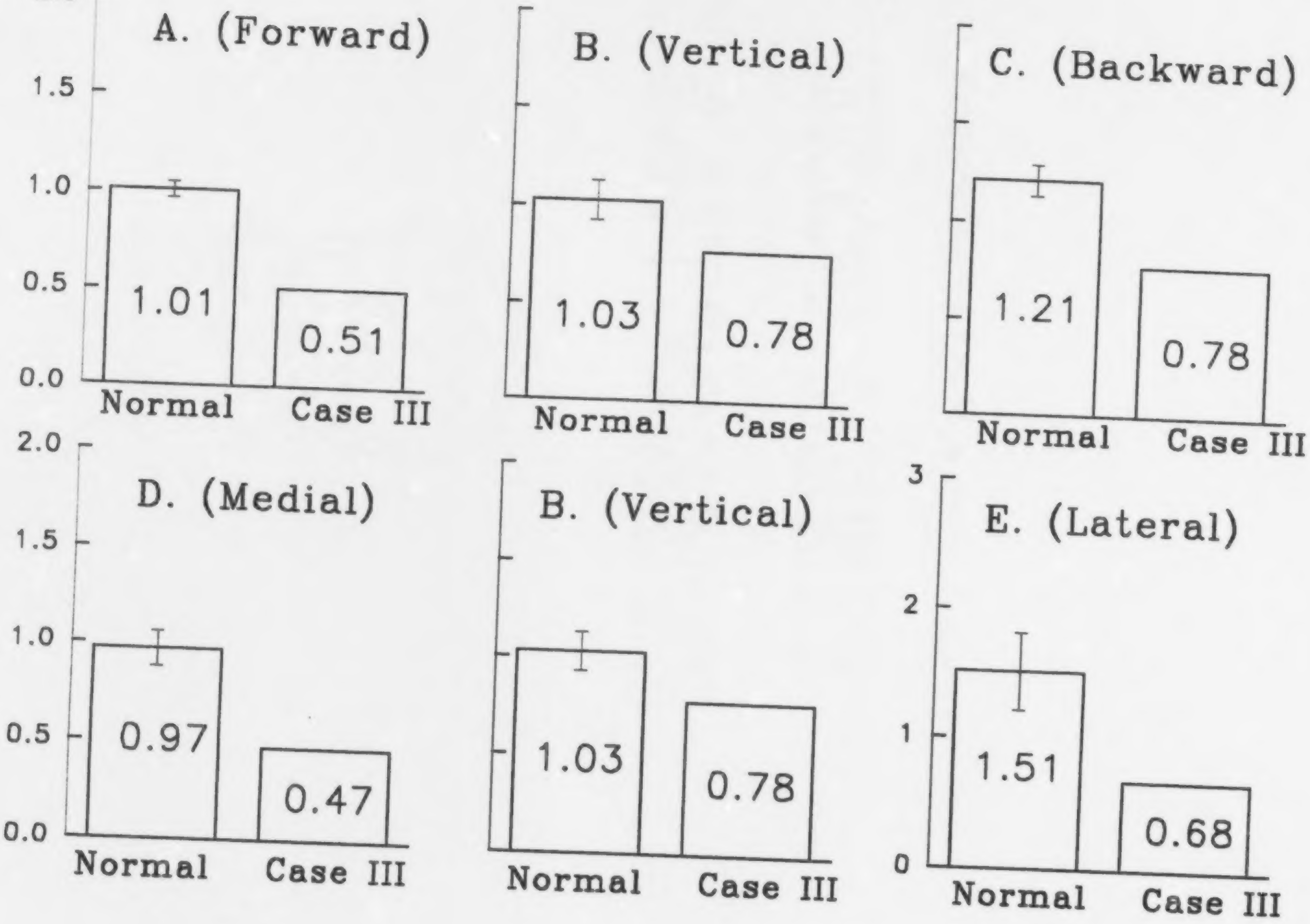
Balancing TM/MA

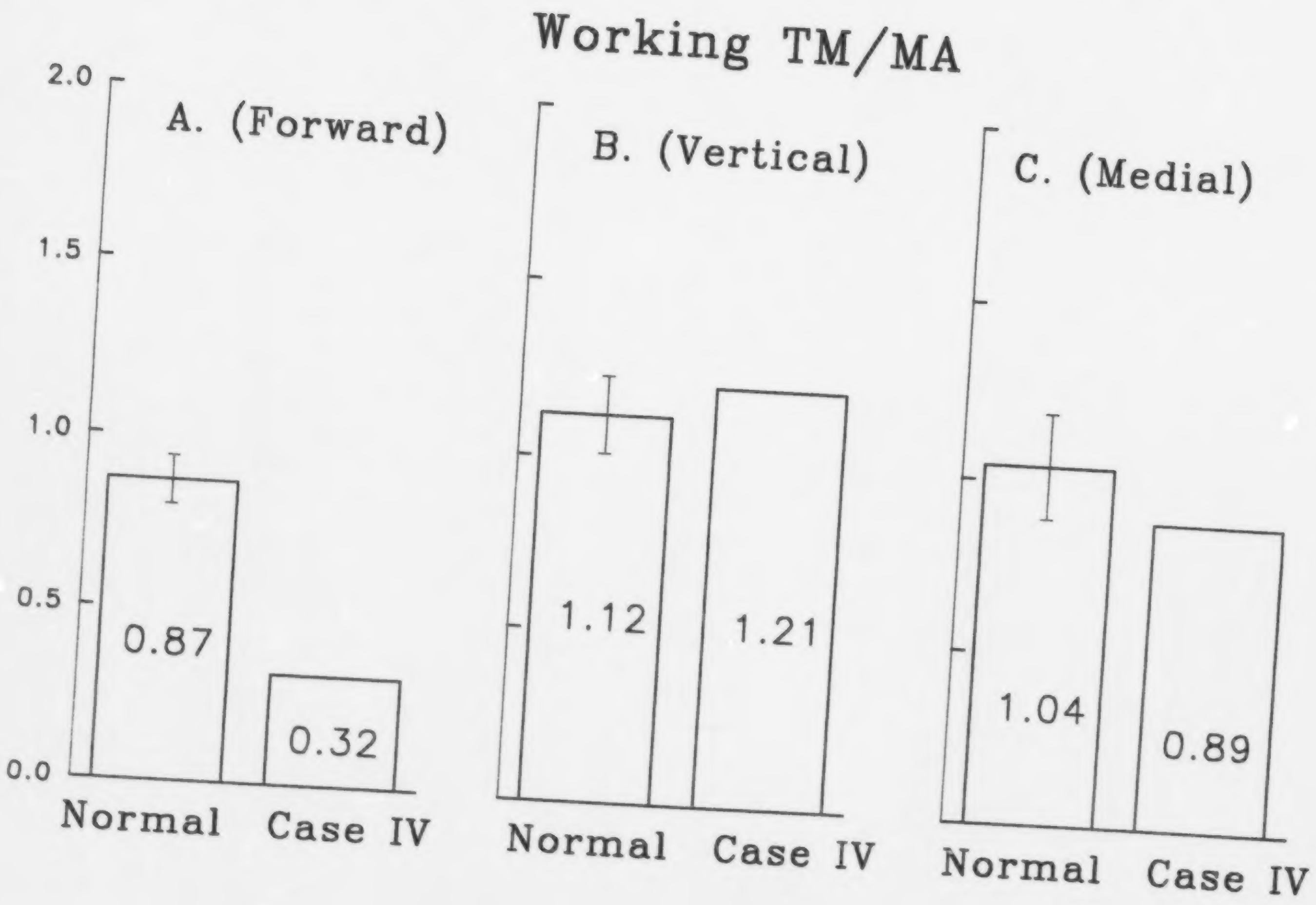


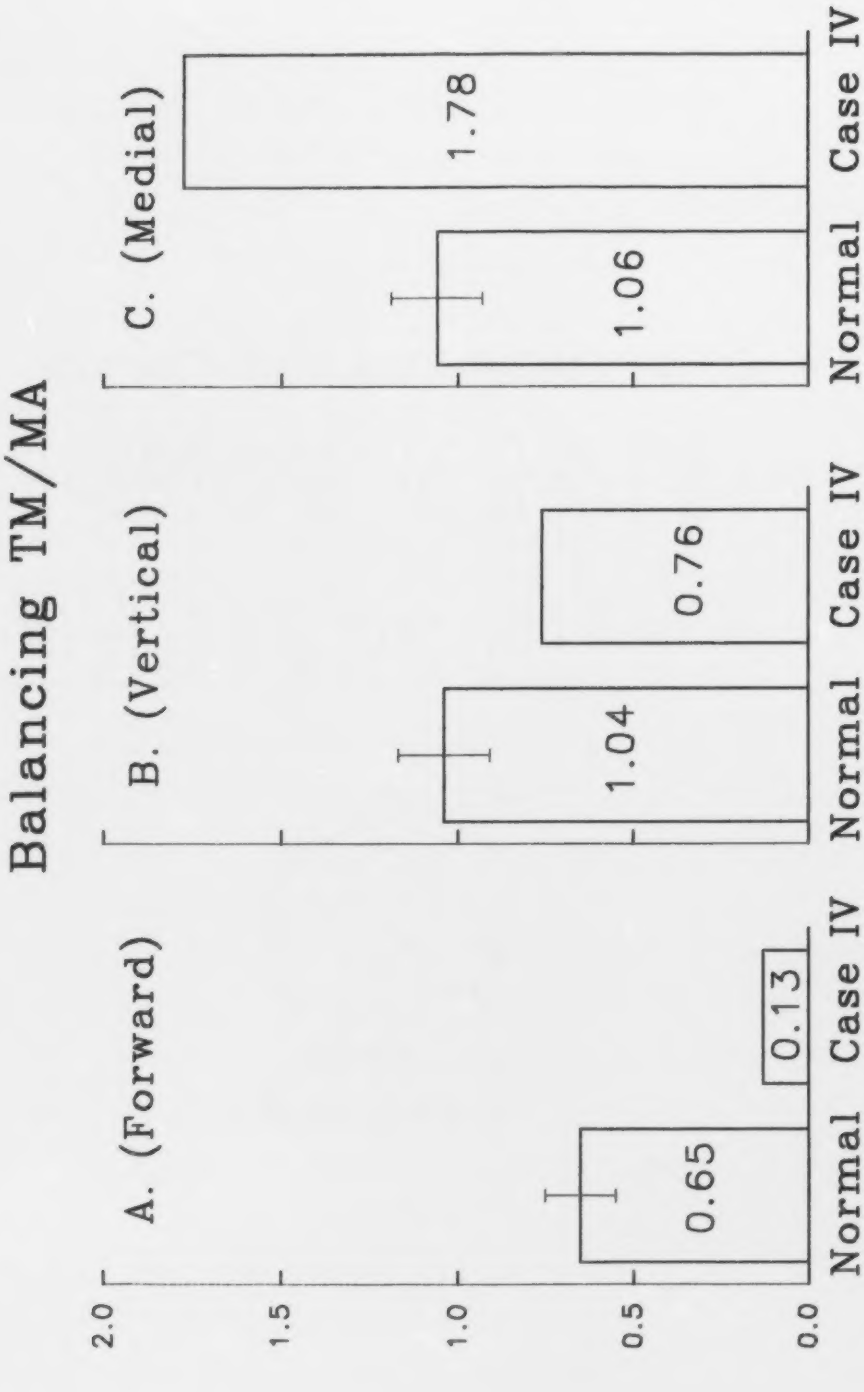
Working/Balancing TMs

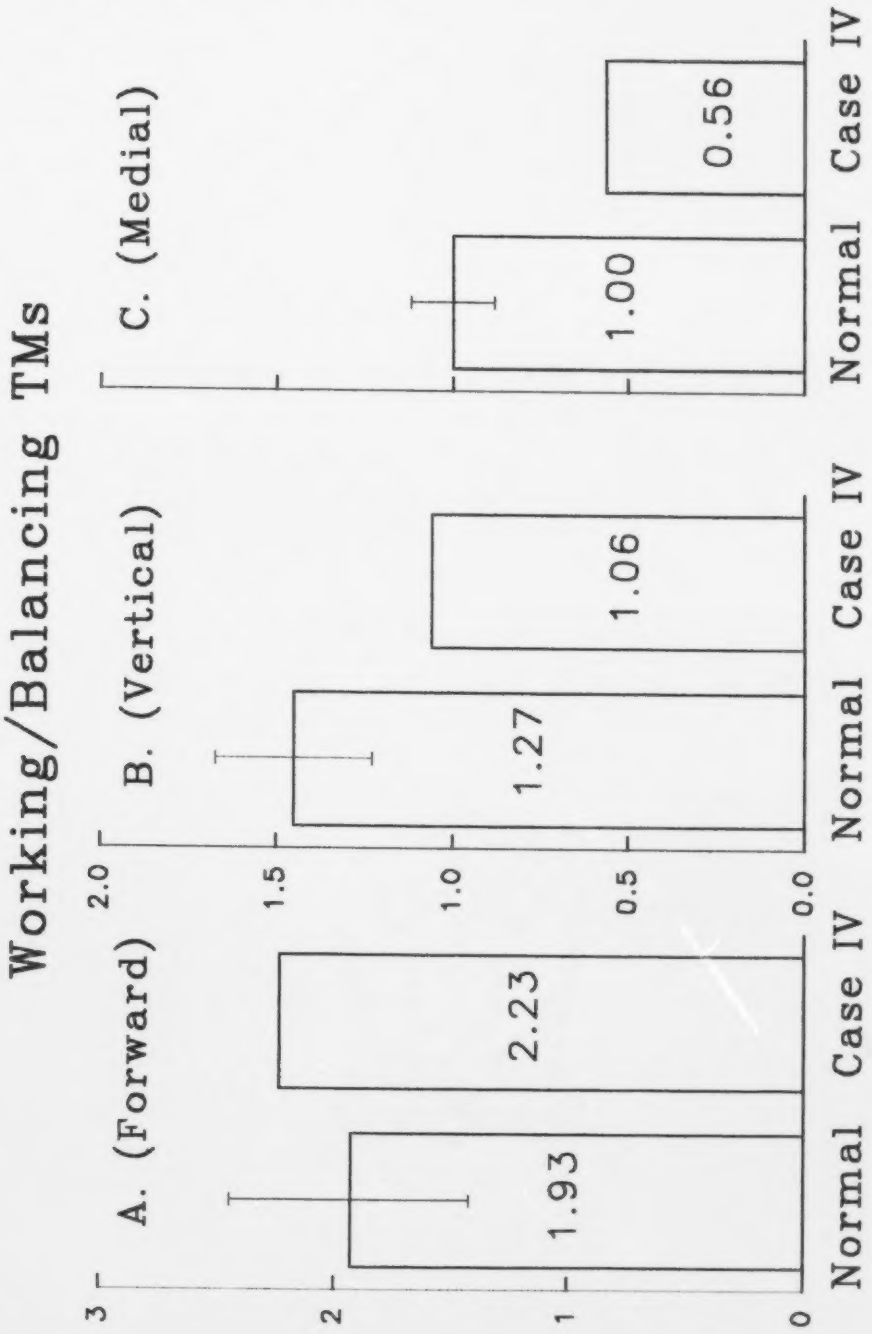


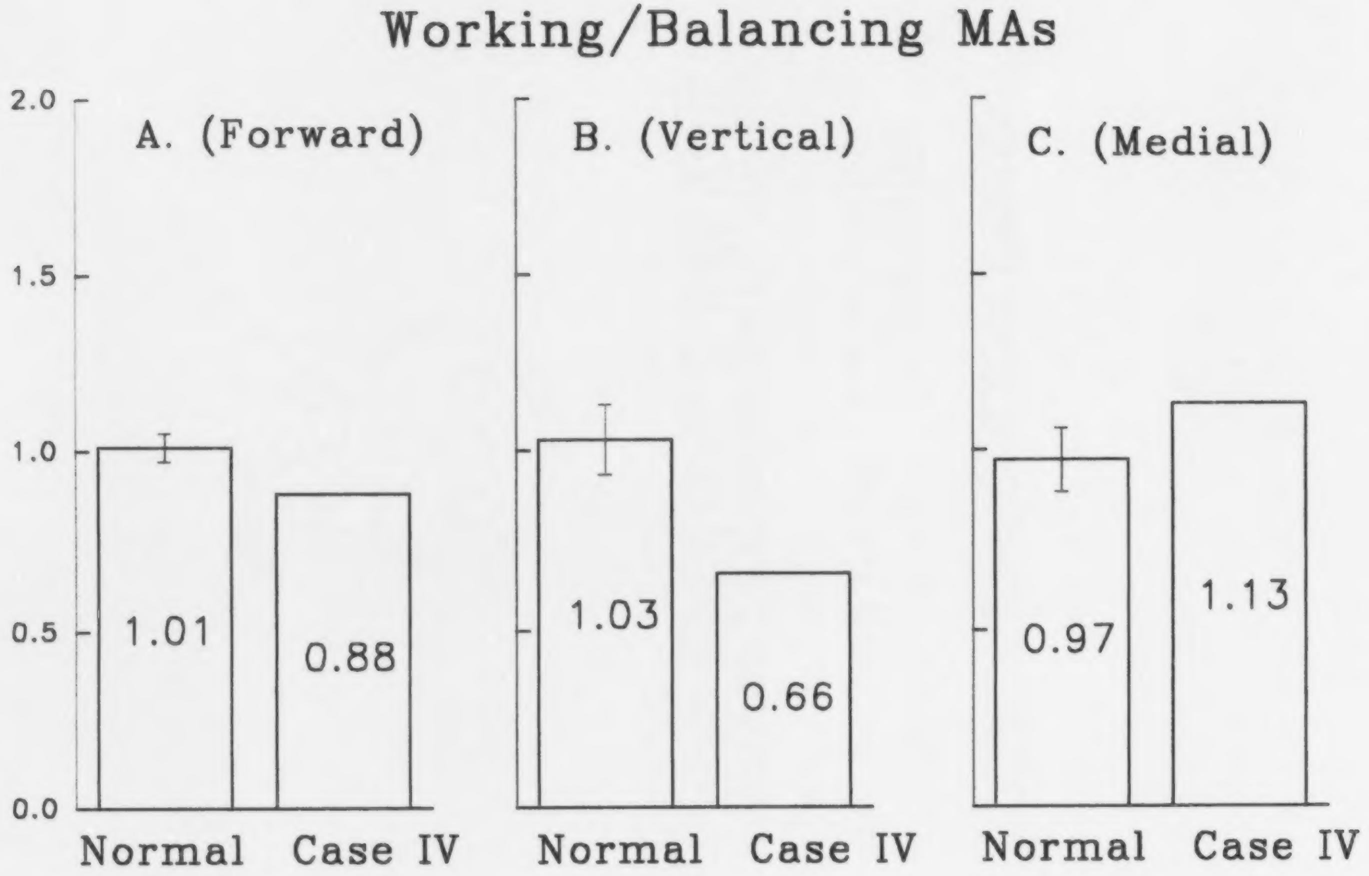
Working/Balancing MAs




Working TM/MA
A. (Forward)
B. (Vertical)
C. (Medial)
2.0
1.5
1.0
0.5
0.0
0.87
0.32
1.12
1.21
1.04
0.89
Normal
Case IV
Normal
Case IV
Normal
Case IV


Balancing TM/MA
A. (Forward)
B. (Vertical)
C. (Medial)
2.0
1.5
1.0
0.5
0.0
0.65
0.13
1.04
0.76
1.06
1.78
Normal
Case IV
Normal
Case IV
Normal
Case IV


Working/Balancing TMs
A. (Forward)
B. (Vertical)
C. (Medial)
3
2
1
0
2.0
1.5
1.0
0.5
0.0
1.93
2.23
1.27
1.06
1.00
0.56
Normal
Case IV
Normal
Case IV
Normal
Case IV



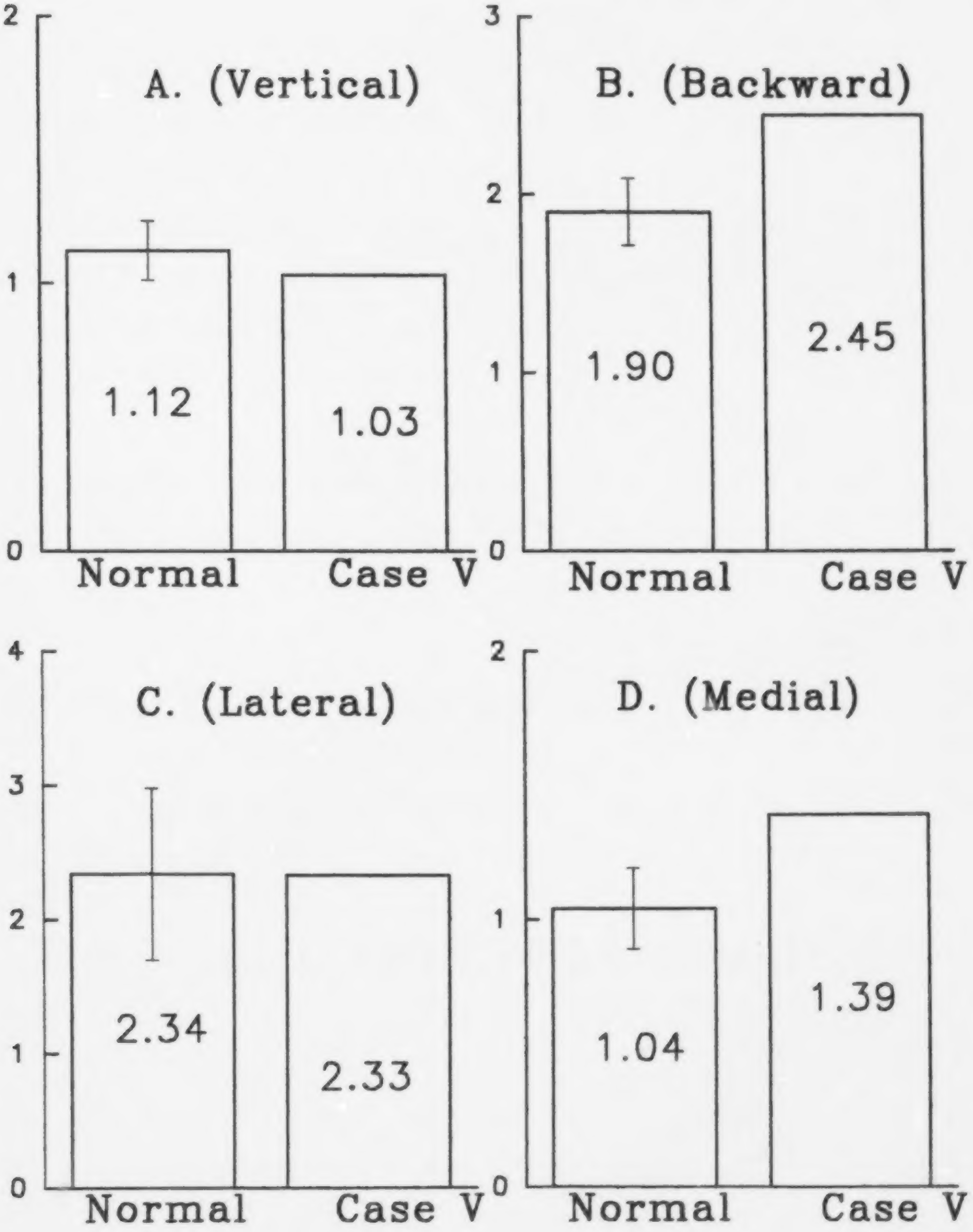
Working/Balancing MAs

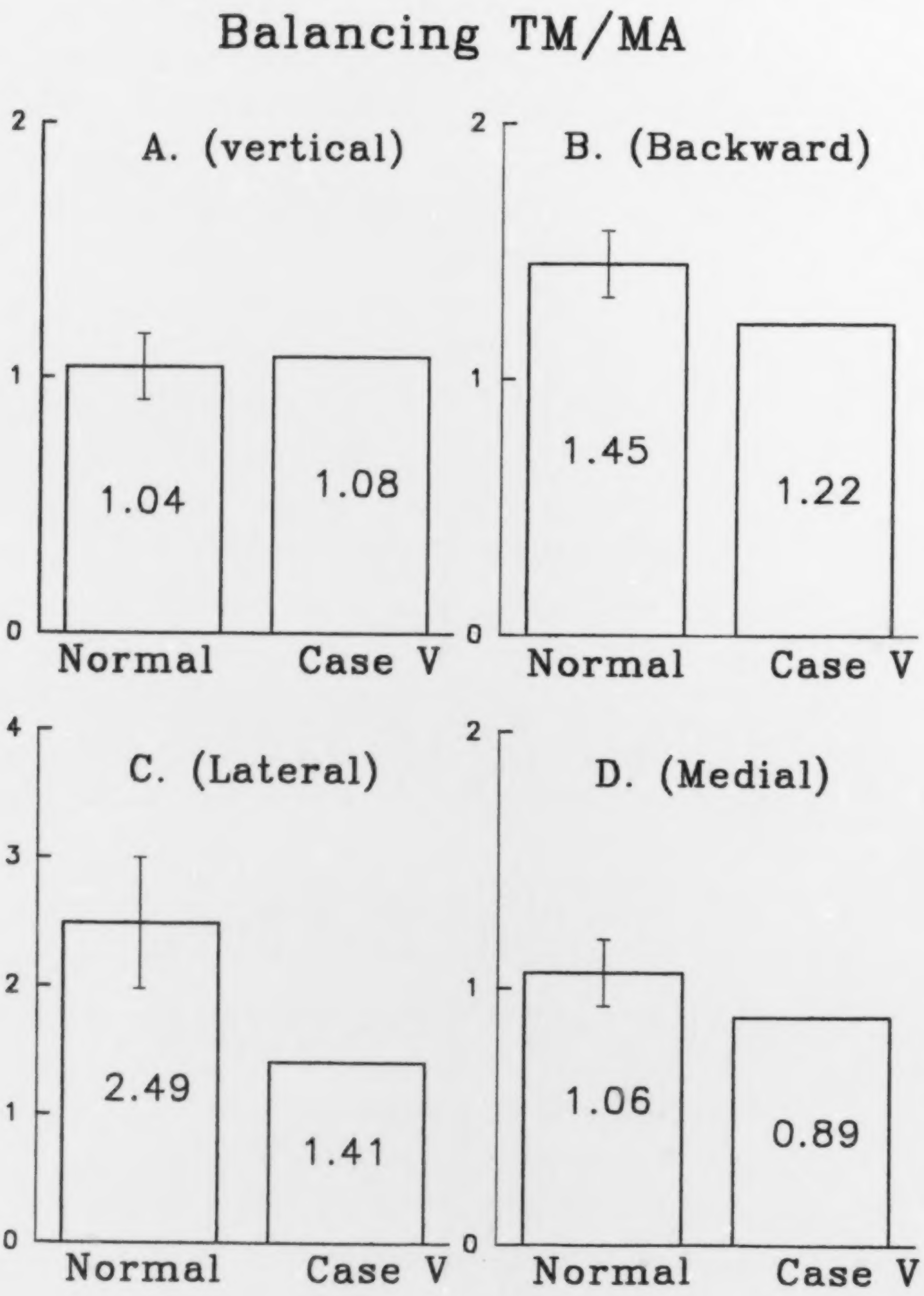
A. (Forward)

B. (Vertical)

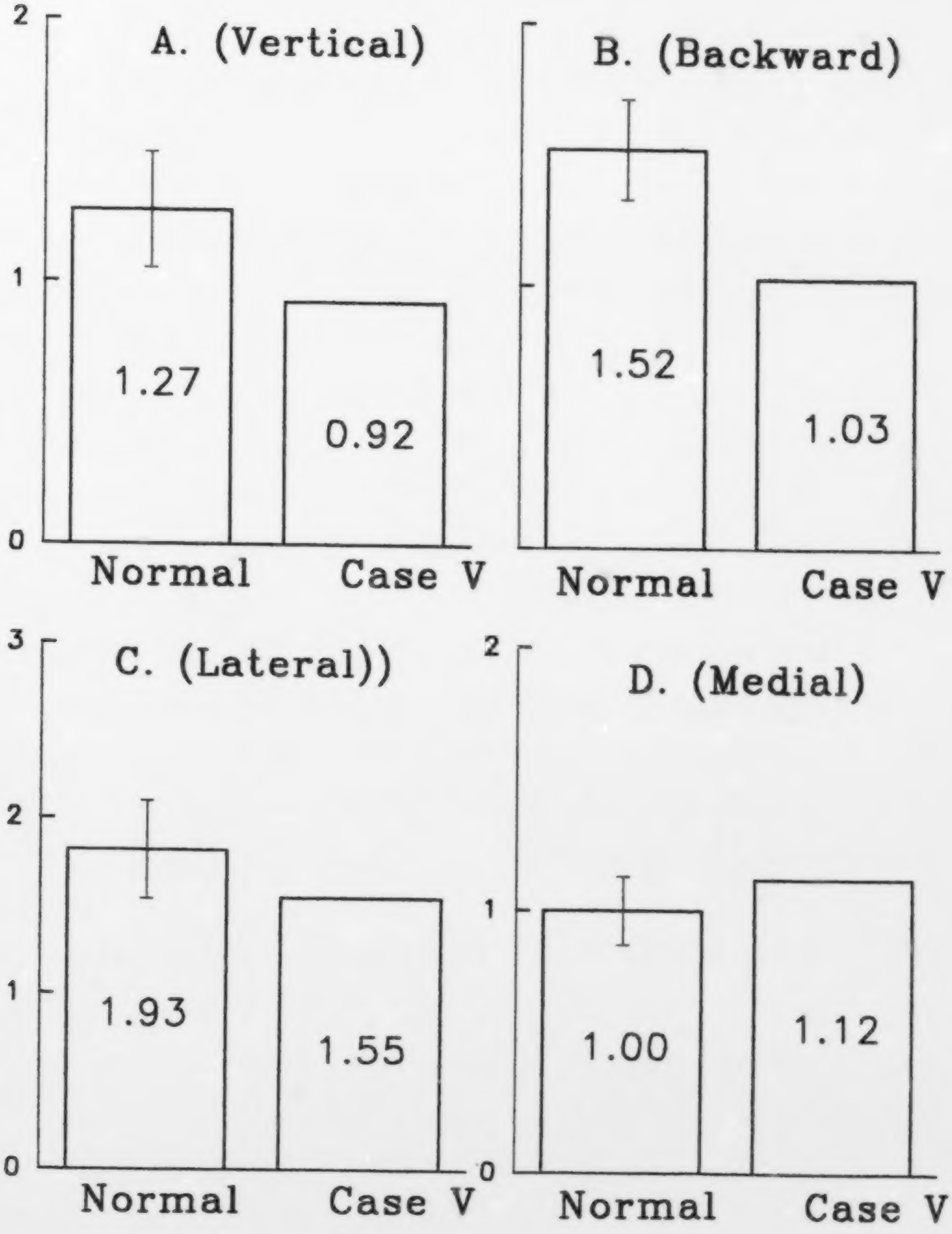
C. (Medial)

Working TM/MA

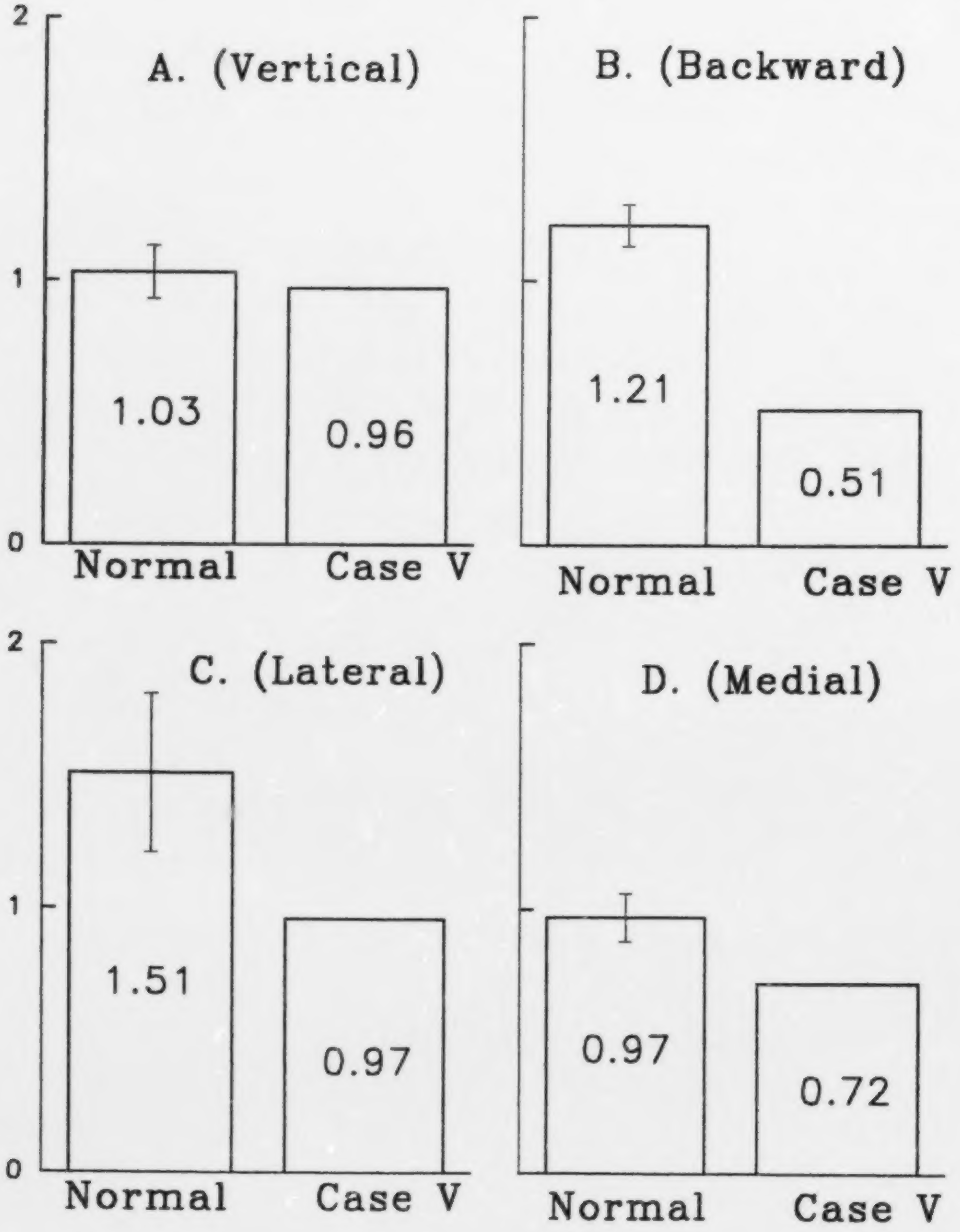


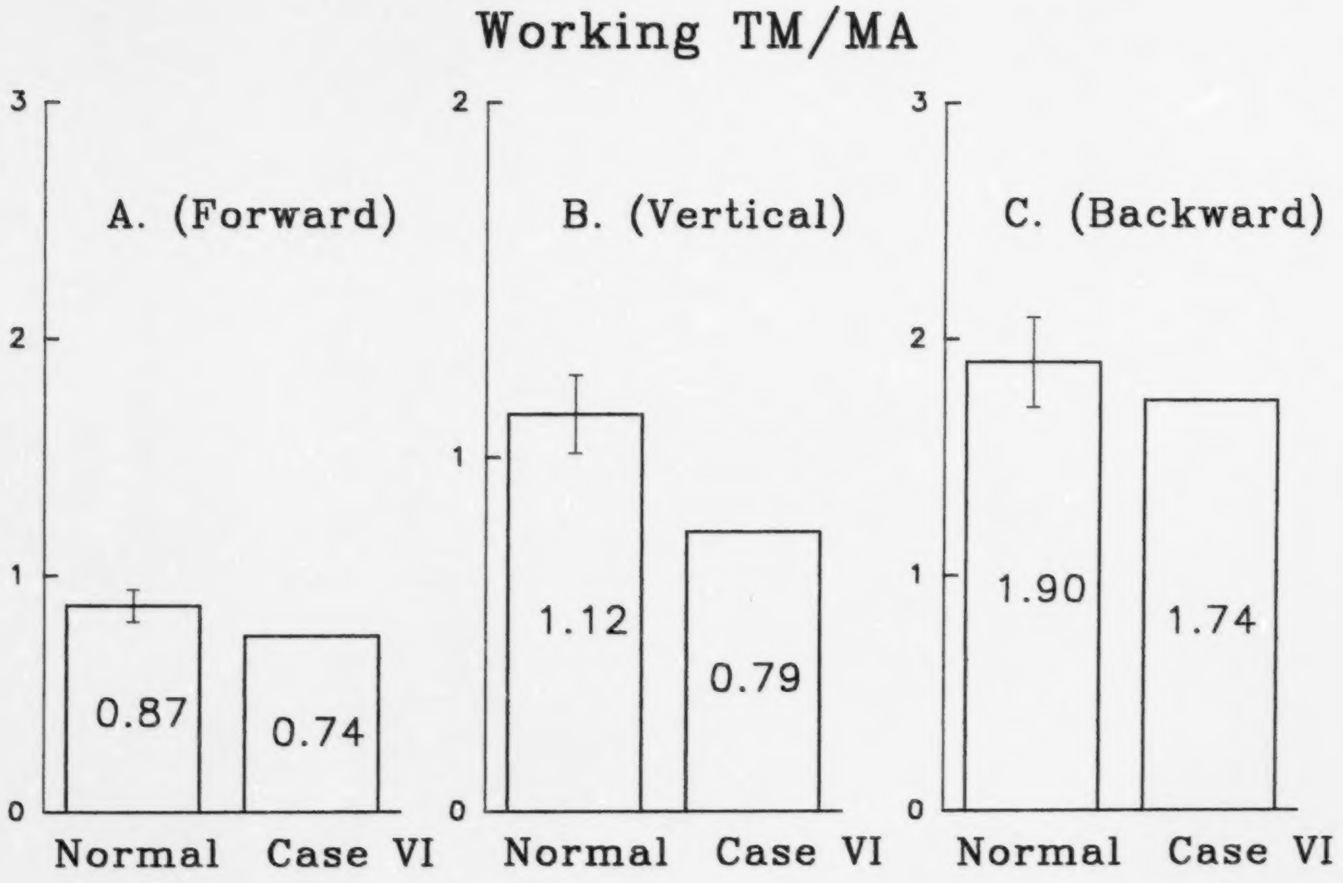

Balancing TM/MA
A. (vertical)
2
1
0
1.04
1.08
Normal
Case V
B. (Backward)
2
1
0
1.45
1.22
Normal
Case V
C. (Lateral)
4
3
2
1
0
2.49
1.41
Normal
Case V
D. (Medial)
2
1
0
1.06
0.89
Normal
Case V

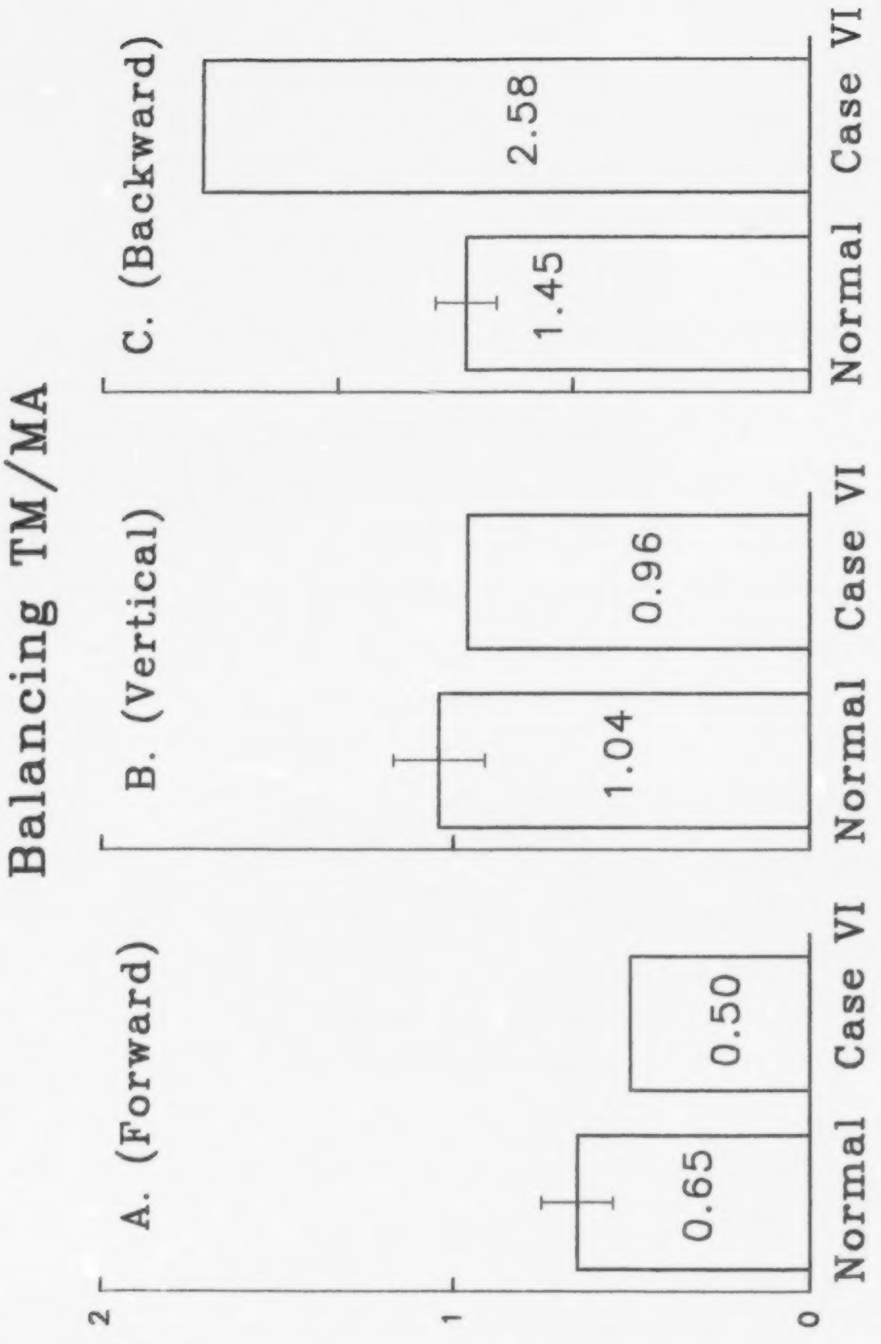
Working/balancing TMs

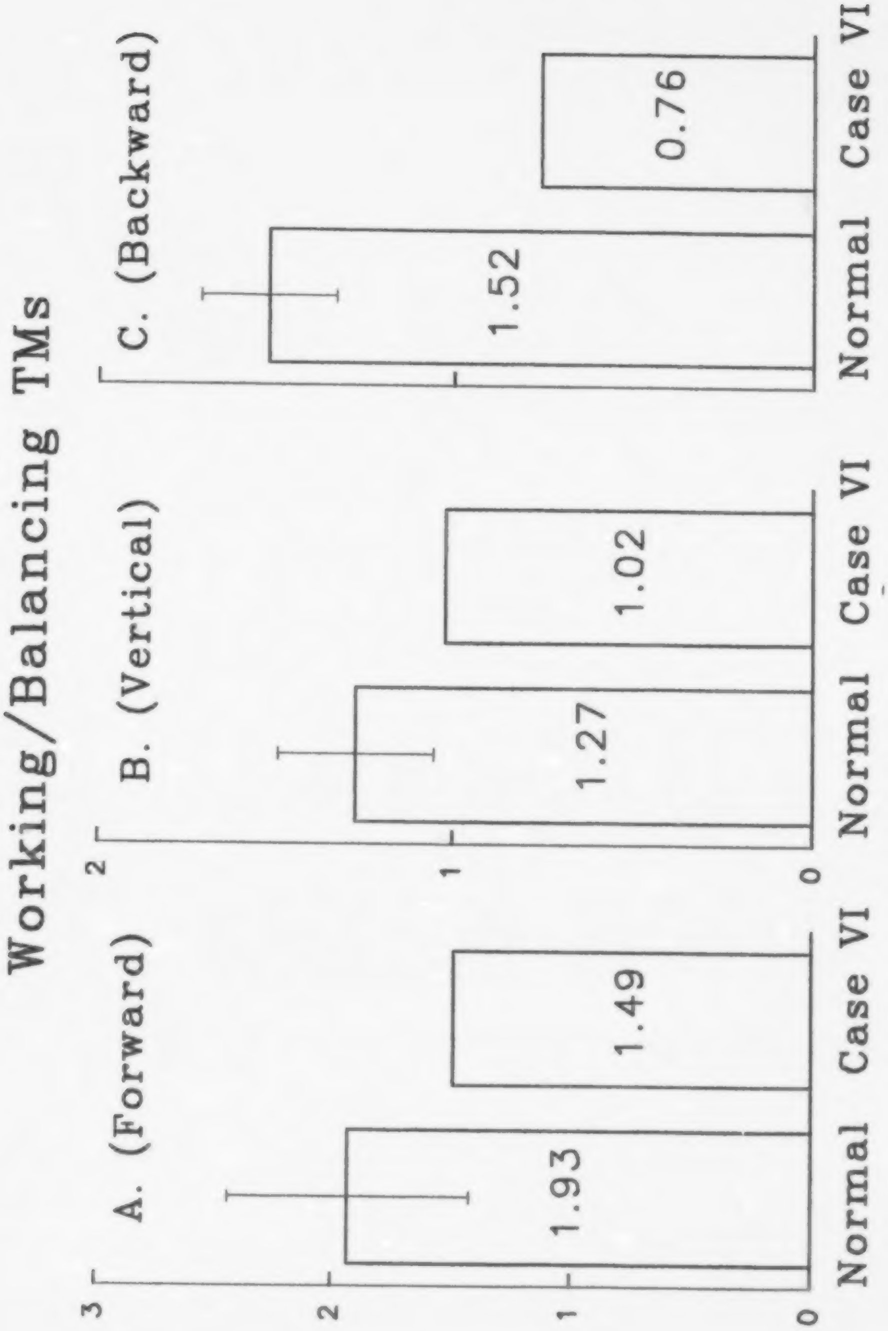


Working/Balancing MAs

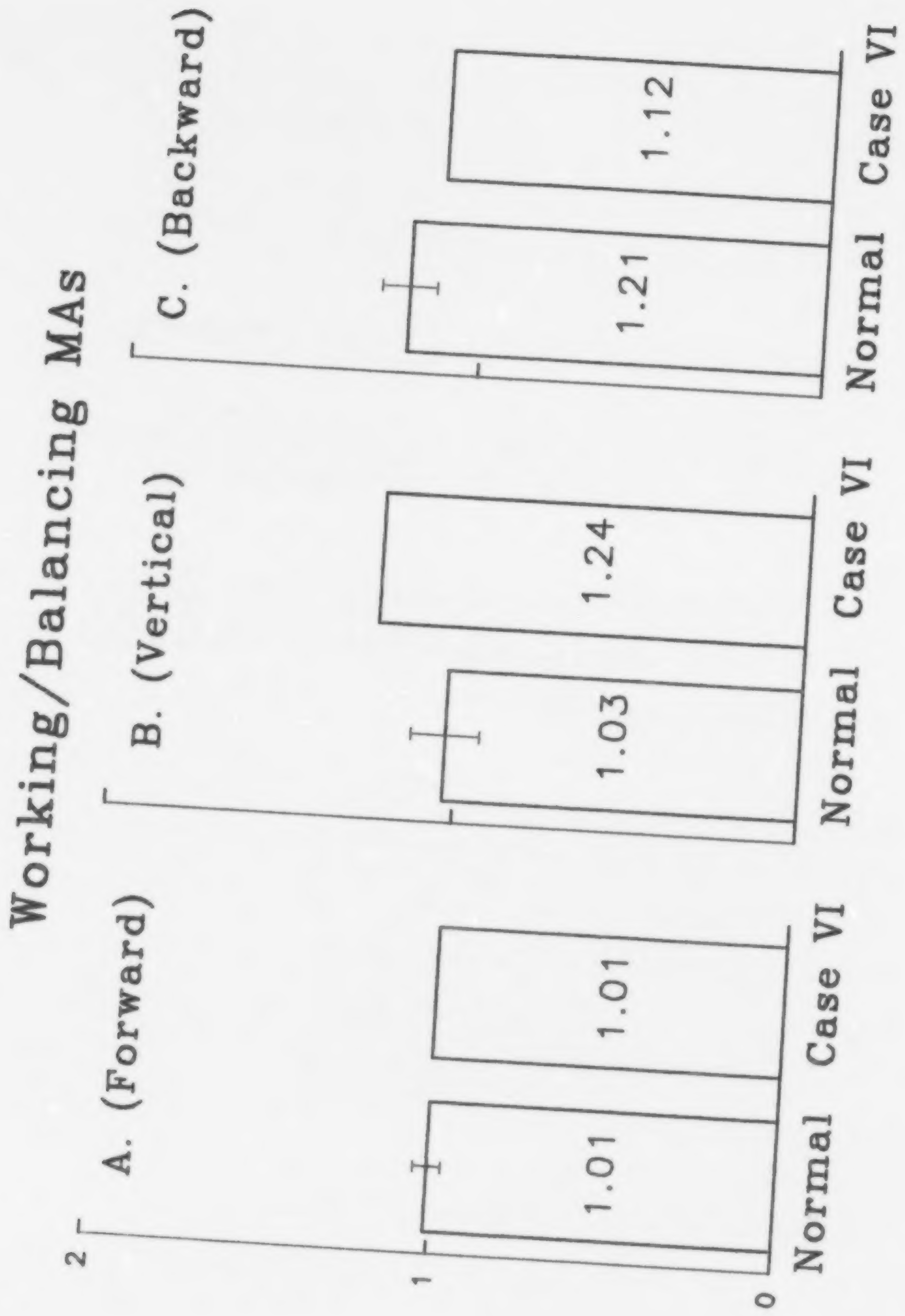


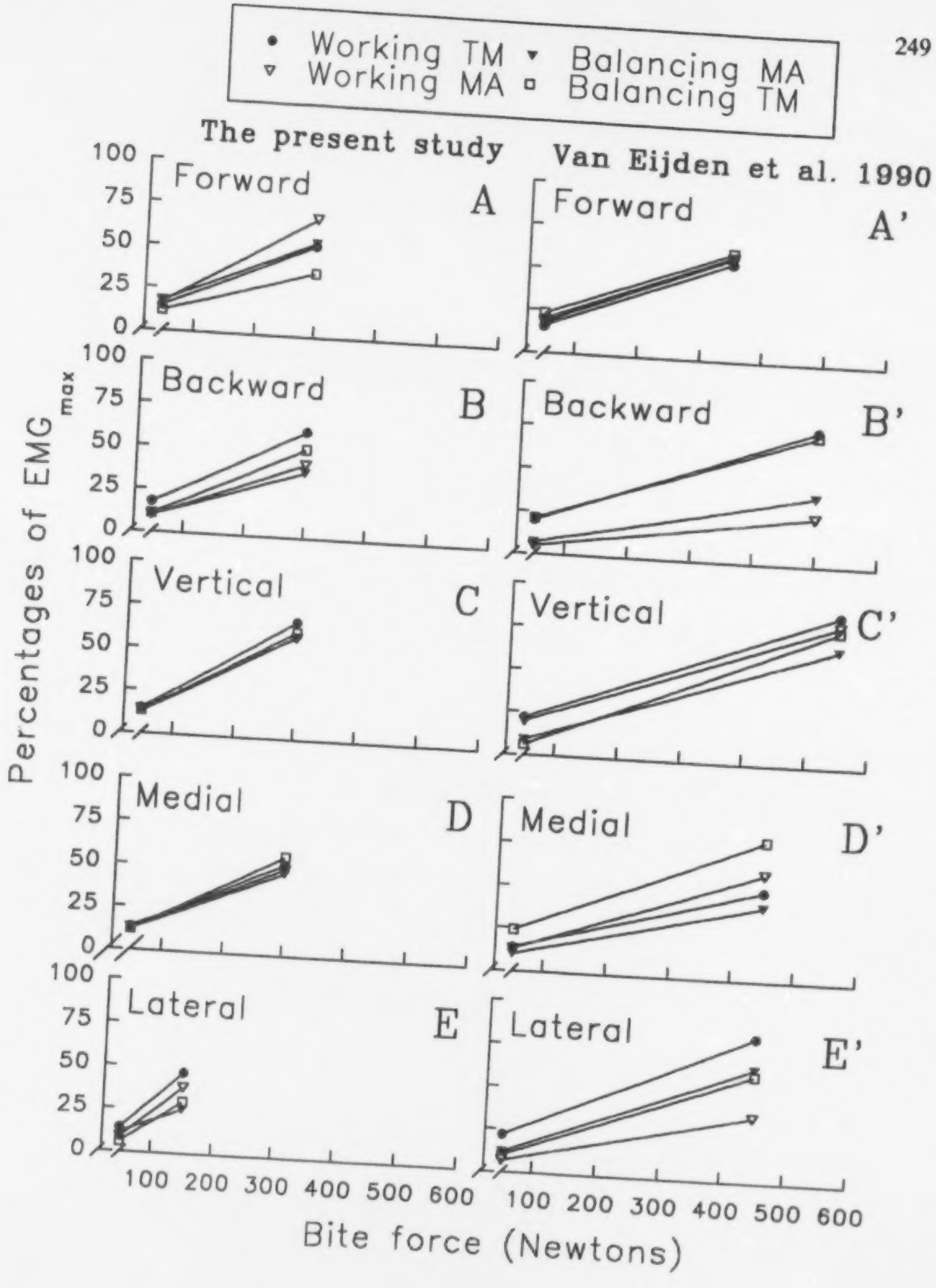

Working TM/MA
A. (Forward)
B. (Vertical)
C. (Backward)
3
2
1
0
0.87
0.74
1.12
0.79
1.90
1.74
Normal
Case VI
Normal
Case VI
Normal
Case VI


Balancing TM/MA
A. (Forward)
B. (Vertical)
C. (Backward)
0
1
2
0.65
0.50
1.04
0.96
1.45
2.58
Normal
Case VI
Normal
Case VI
Normal
Case VI



Working/Balancing TMs


Working/Balancing MAs
A. (Forward)
B. (Vertical)
C. (Backward)
2
1
0
1.01
1.01
1.03
1.24
1.21
1.12
Normal
Case VI
Normal
Case VI
Normal
Case VI


● Working TM
▼ Balancing MA
▽ Working MA
□ Balancing TM
The present study
Van Eijden et al. 1990
Forward
A
Forward
A'
Backward
B
Backward
B'
Vertical
C
Vertical
C'
Medial
D
Medial
D'
Lateral
E
Lateral
E'
100
75
50
25
0
Percentages of EMG$_{max}$
100 200 300 400 500 600
Bite force (Newtons)

Bibliography

Adler P (1947) Sensibility of teeth to loads in different directions. *J Dent Res* **26**, 279-289.

Ahlgren J (1969) The silent period in the EMG of the jaw muscles during mastication and its relationship to tooth contact. *Acta Odont Scand* **27**, 219-227.

Ahlgren J, Owall W (1970) Muscular activity and chewing force: a polygraphic study of human mandibular movements. *Arch Oral Biol* **15**, 271-280.

Ahlgren J, Sonesson B, Blitz M (1985) An electromyographic analysis of the temporalis function of normal occlusion. *Am J Orthod* **87**, 230-239.

Ahlgren J, Henrikson T (1987) A comparison of electromyography recorded parallel and transverse to the fibres of the anterior and posterior temporalis muscle in man. *Arch Oral Biol* **32**, 685-687.

Anderson DJ (1953) A method of recording masticatory loads. *J Dent Res* **32**, 785-789.

Anderson DJ (1956*a*) Measurement of stress in mastication, I. *J Dent Res* **35**, 664-670.

Anderson DJ (1956*b*) Measurement of stress in mastication, II. *J Dent Res* **35**, 671-673.

Ash MM Jr., Ramfjord SP (1982) *Introduction to functional occlusion*. WB Saunders, Philadelphia.

Ash MM Jr. (1986) Current concepts in the aetiology, diagnosis and treatment of TMJ and muscle dysfunction. *J Oral Rehab* **13**, 1-20.

Bailey JO, McCall WD, Ash MM Jr. (1977) Electromyographic silent periods and jaw motion parameters: quantitative measures of temporomandibular joint dysfunction. *J Dent Res* **56**, 249-253.

Bakke M, Michler L, Han K, Moller E (1989) Clinical significance of isometric bite force versus electrical activity in temporal and masseter muscles. *Scand J Dent Res* **97**, 539-551.

References

Bakke M, Michler L, Han K, Moller E (1990) Unilateral, isometric bite force in 8-68-year-old women and men related to occlusal factors. *Scand J Dent Res* **98**, 149-158.

Baragar FA, Osborn JW (1984) A model relating patterns of human jaw movement to biomechanical constraints. *J Biome* **17**, 757-767.

Baragar FA, Osborn JW (1987) Efficiency as a predictor of human jaw design in the sagittal plane. *J Biomech* **20**, 447-457.

Bell WE (1989) *Orofacial Pains. Classification, Diagnosis, Management.* 4th ed. Chicago, Year Book Medical Publishers.

Bernshtein VM (1967) Statistical parameters of the electrical signal of a muscle model. *Biophysics* **12**, 801-813.

Bessete R, Bishop B, Mohl N (1971) Duration of masseteric silent period in patients with TMJ syndrome. *J Appl Physiol* **30**, 864-869.

Bigland B, Lippold OCJ (1954) The relation between force, velocity and integrated electrical activity in human muscles. *J Physiol (Lond)* **123**, 214-224.

Blanksma NG, van Eijden TMGJ (1990) Electromyographic heterogeneity in the human temporalis muscle. *J Dent Res* **69**, 1,686-1,690.

Boero RP (1989) The physiology of splint therapy: a literature review. *Angle Orthod* **59**, 165-180.

Boos RH (1940) Intermaxillary relation established by biting power. *J Am Dent Assoc* **27**, 1,192-1,199.

Boucher LJ, Zwemer TJ, Pflughoeft F (1959) Can biting force be used as a criterion for registering vertical dimension? *J Prosthet Dent* **9**, 594-599.

Bratzlavsky M (1976) In: Anderson DJ, Matthews B (eds) *Mastication*. John Wright and Sons Ltd., Bristol, UK. *pp*. 147-152.

Brekhus PJ, Armstrong WD, Simon WJ (1941) Stimulation of the muscles of mastication. *J Dent Res* **20**, 87-92.

Broekhuijsen ML, van Willingen JD (1983) Factors influencing jaw position sense in man. *Arch Oral Biol* **28**, 387-391.

Buchanan TS, Almdale DP, Lewis JL, Rymer WZ (1986) Characteristics of synergic relations during isometric contractions of human elbow muscles. *J Neurophysiol* **56**, 1,225-1,241.

Buchanan TS, Roval GP, Rymer WZ (1989) Strategies for muscle activation during isometric torque generation at the human elbow. *J Neurophysiol* **62**, 1,201-1,212.

Burdette BH, Gale EN (1990) Reliability of surface electromyography of the masseteric and anterior temporal areas. *Arch Oral Biol* **35**, 747-751.

Calancie B, Bawa P (1990) Motor unit recruitment in humans. In: *The Segmental Motor System*. Binder MD, Mendell LM (eds.). Oxford University Press, Inc., New York, USA. *pp*. 75-95.

Campbell HG (1977) *An Introduction to Matrices, Vectors, and Linear Programming.* 2nd ed., Pentice-Hall, Inc., Englewood Cliffs, New Jersey, USA. *pp*. 280.

Carlsöö S (1952) Nervous coordination and mechanical function of the mandibular elevators: an EMG study of the activity and anatomic analysis of the mechanics of the muscle. *Acta Odont Scand* **10 (suppl)**, p. 43.

Carlsöö S (1956) An electromyographic study of the activity, and an anatomic analysis of the mechanics of the lateral pterygoid muscle. *Acta Anat* **26**, 339-351.

Carlsson GE (1974) Bite force and chewing efficiency. In Kawamura Y (ed.) *Frontiers of Oral Physiology*. Vol. 1. Baser:Karger. pp. 265-292.

Christensen LV (1980) Effects of an occlusal splint on integrated electromyography of masseter muscle in experimental tooth clenching. *J Oral Rehab* **7**, 281-288.

Christensen LV (1981) Facial pains and the jaw muscles: a review. *J Oral Rehab* **8**, 193-201.

Christensen LV, Radue JT (1985*a*) Lateral preference in mastication: a feasibility study. *J Oral Rehab* **12**, 421-427.

Christensen LV, Radue JT (1985*b*) Lateral preference in mastication: an electromyographic study. *J Oral Rehab* **12**, 429-434.

Christensen LV, Radue JT (1985*c*) Isometric endurance of the human masseter muscle during consecutive bouts of tooth clenching. *J Oral Rehab* **12**, 509-514.

Clark GT, Beemsterboer PL, Solberg WK, Rugh JD (1979) Nocturnal electromyographic evaluation of myofascial pain dysfunction in patients undergoing occlusal splint therapy. *J Am Dent Assoc* **99**, 607-611.

Clark GT (1984*a*) A critical evaluation of orthopedic interocclusal appliance therapy: Design, theory, and overall effectiveness. *J Am Dent Assoc* **108**, 359-364.

Clark GT (1984*b*) A critical evaluation of orthopedic interocclusal appliance therapy: effectiveness for specific symptoms. *J Am Dent Assoc* **108**, 364-368.

Clark GT, Carter MC (1985) Electromyographic study of human jaw-closing muscle endurance, fatigue and recovery at various isometric force levels. *Arch Oral Biol* **30**, 563-569.

Clark GT, Lynn P (1986) Horizontal plane jaw movements in control and TMJ clinic patients. *J Prosthet Dent* **55**, 730-735.

Clark GT, Carter MC, Beemsterboer PL (1988) Analysis of electromyographic signals in human jaw closing muscles at various isometric force levels, *Arch Oral Biol* **33**, 833-837

Clark GT, Jow RW, Lee JJ (1989*a*) Jaw pain and stiffness levels after repeated sustained maximum voluntary clenching. *J Dent Res* **68**, 69-71.

Clark GT, Seligman DA, Solberg WK, Pullinger AG (1989*b*) Guidelines for the examination and diagnosis of temporomandibular disorders. *J Craniomand Disorders Facial Oral Pain* **3**, 7-14.

Close JR (1964) Motor Function on the Lower Extremity. *American Lecture Series 551*, Thomas, Springfield.

Close RI (1972) Dynamic properties of mammalian skeletal muscles. *Physiol Rev* **52**, 129-197.

Cobbold RSC (1986) *Transducers for Biomedical Measurements: Principles and Applications.* John Wiley & Sons Inc., New York, NY USA.

Coffey JP, Williams WN, Turner GE, Mahan PE, LaPointe LL, Cornell CE (1989) Human bite force discrimination using specific maxillary and mandibular teeth. *J Oral Rehab* **16**, 529-536.

Dahl BL, Floystrand, F, Karlsen K (1985) Pathologic attrition and maximal bite force. *J Oral Rehab* **12**, 337-342.

Dahlström L, Haraldson T (1985) Bite plates and stabilization splints in mandibular dysfunction. A clinical and electromyographic comparison. *Acta Odont Scand* **43**, 109-114.

Dahlström L, Haraldson T, Janson ST (1985*a*) Comparative electromyographic study of bite plates and stabilization splints. *Scand J Dent Res* **93**, 262-268.

Dahlström L, Carlsson SG, Gale EN, Jansson TG (1985*b*) Stress-induced muscular activity in mandibular dysfunction. *J Behav Med* **8**, 191-200.

Dahlström L, Tzakis M, Haraldson T (1988) Endurance tests of the masticatory system on different bite force levels. *Scand J Dent Res* **96**, 137-142.

Dahlström L (1989) Electromyographic studies of craniomandibular disorders: a review of literature. *J Oral Rehab* **16**, 1-20.

Dahlström L, Haraldson T (1989) Immediate electromyographic response in masseter and temporal muscles to bite plates and stabilization splints. *Scand J Dent Res* **97**, 533-538.

Dahlström L, Haraldson T, Carlsson GE (1989) Perception of jaw position during different conditions. *J Craniomand Disord Facial Oral Pain* **3**, 147-151.

Dally JW, Riley WF (1965) Strain and stress-strain relations. In: *Experimental Stress Analysis*. 1st ed. McGraw-Hill Co., New York. *p*. 55.

Dally JW, Riley WF (1978) Analysis of strain-gage data. Chapter 10 In: *Experimental Stress Analysis*. 2nd ed. McGraw-Hill Co., New York. *pp*. 318-336.

Davis DD (1964) The Giant Panda. *Fiediana*: Zoology Memoirs, Vol.3.

De Boever JA, McCall Jr WD, Holden S, Ash MM (1978) Functional occlusal forces: an investigation by telemetry. *J Prosthet Dent* **40**, 326-333.

Dechow PC, Carlson DS (1983) A method of bite force measurement in primates. *J Biomech* **10**, 797-802.

De Luca CJ (1979) Physiology and mathematics of myoelectric signals. *IEEE Trans Biomed Eng* **26**, 313-325.

Desmedt JE, Godaux E (1979) Recruitment patterns of single motor units of the human masseter muscle during brisk jaw clenching. *Arch Oral Biol* **24**, 171-178.

Desmedt JE (1980) Patterns of motor commands during various types of voluntary movement in man. *Trends in Neurosci* **3**, 265-268.

Dessem D, Iyadurai OD, Taylor A (1988) The role of periodontal receptors in the jaw-opening reflex in the cat. *J Physiol* (Lond) **406**, 315-330.

Dessem D (1989) Interactions between jaw-muscle recruitment and jaw-joint forces in *Canis familiaris*. *J Anat* **164**, 107-121.

Devlin H, Wastell DG (1985) Bite force and masseter muscle electromyographic activity during onset of an isometric clench in man. *Arch Oral Biol* **30**, 213-215.

Dowben RM (1980) Contractility. In *Medical Physiology*. pp. 89. Mountcastle VB (ed.) C.V. Mosby Co., St. Louis, MI, USA

Dul J, Townsend MA, Shiavi R, Johnson GE (1984*a*) Muscular synergism - I: on criteria for load sharing between synergistic muscles. *J Biomech* **17**, 663-673.

Dul J, Townsend MA, Shiavi R, Johnson GE (1984*b*) Muscular synergism - II: A minimum-fatigue criterion for load sharing between synergistic muscles. *J Biomech* **17**, 675-684.

Duxbury AJ, Frame JW, Rothwell PS, Jackson PD (1973) An instrument for the measurement of incisive bite force. *J Dent* **1**, 246-250.

Edstrom L, Grimby L (1986) Effects of exercise on the motor unit. *Muscle & Nerve* **9**, 104-126.

Edwards RHT, Lippold OCJ (1956) The relation between force and integrated electrical activity in fatigued muscle. *J Physiol (Lond)* **132**, 677-681.

English AW, Letbetter WD (1982*a*) Anatomy and innervation patterns of cat lateral gastrocnemius and plantaris muscles. *Am J Anat* **164**, 67-77.

English AW, Letbetter WD (1982*b*) A histochemical analysis of identified compartments in cat lateral gastrocnemius muscle. *Anat Rec* **204**, 123-130.

English AW (1984) An electromyographic analysis of compartments of cat lateral gastrocnemius muscle during unrestrained locomotion. *J Neurophysiol* **52**, 114-125.

English AW, Weeks OI (1984) Compartmentalization of single motor units in cat lateral gastrocnemius. *Exp Brain Res* **56**, 361-368.

English AW (1985) Jaw *vs.* limb muscles: can they be compared? *Am Zool* **25**, 351-363.

Eriksson P-O, Stalberg E, Antoni L (1984) Flexibility in motor-unit pattern in the human temporal and masseter muscles related to type of activation and location. *Arch Oral Biol* **29**, 701-712.

Evarts EV, Fromm C, Kroller J, Jennings VA (1983) Motor cortex control of finely graded forces. *J Neurophysiol* **49**, 1,199-1,215.

Faulkner JA, McCully KK, Carlson DS, McNamara JA (1982) Contractile properties of the muscles of mastication of rhesus monkeys (*Macaca mulatta*) following increase in muscle length. *Arch Oral Biol* **27**, 841-845.

Fields HW, Proffit WR, Case JC, Vig KWL (1986) Variables affecting measurements of vertical occlusal force. *J Dent Res* **65**, 135-138.

Flanders M, Soechting JF (1990) Arm muscle activation for static forces in three-dimensions. *J Neurophysiol* **64**, 1,818-1,873.

Floystrand F, Kleven E, Oilo G (1982) A novel miniature bite force recorder and its clinical application. *Acta Odont Scand* **40**, 209-214.

Fricton JR, Schiffman EL (1986) Reliability of a craniomandibular index. *J Dent Res* **65**, 1,359-1,364.

Fricton JR, Schiffman EL (1987) The craniomandibular index: validity. *J Prosthet Dent* **58**, 222-228.

Fuchs P (1975) The muscular activity of the chewing apparatus during night sleep. *J Oral Rehab* **2**, 35-48.

Fuglsang-Frederikson A, Lo Monaco M, Dahl K (1984) Integrated electrical activity and number of zero crossings during a gradual increase in muscle force in patients with neuromuscular diseases. *Electroencephalogr and Clin Neurophysiol* **58**, 211-220.

Gans C, Gaunt AS (1992) Muscle architecture in relation to function. *J Biomech* **24 (Suppl)**, 53-65.

Garner LD, Kotwal NS (1973) Correlation study of incisive biting forces with age, sex, and anterior occlusion. *J Dent Res* **52**, 698-702.

Garret FA, Angelone L, Allen WI (1964) The effect of bite opening, bite pressure, and malocclusion on the electrical response of the masseter muscles. *Am J Orthod* **50**, 435-444.

Gelb M (1990) Length-tension relations of the masticatory elevator muscles in normal subjects and pain dysfunction patients. *J Craniomand Practice* **8**, 139-153.

Geogopoulos AP, Kalaska JF, Caminiti R, Massey JT (1982) On the relations between the direction of two-dimensional arm movements and cell discharge in primate motor cortex. *J Neurosci* **2**, 1,527-1,537.

Geogopoulos AP, Caminiti R, Kalaska JF, Massey JT (1983) Spatial coding of movement: A hypothesis concerning the coding of movement direction by motor cortical populations. In: Massion J, Paillard J, Schultz W, Weisendanger M (eds.) *Exp Brain Res Suppl 7: Neural Coding of Motor Performance*. Springer-Verlag. *pp*. 327-336.

Geogopoulos AP, Schwartz AB, Kettner RE (1986) Neuronal population coding of movement direction. *Science* **233**, 1,416-1,419.

Geogopoulos AP, Kettner RE, Schwartz AB (1988) Primate motor cortex and free arm movements to visual targets in three-dimensional space. II. Coding of the direction of movement by a neuronal population. *J Neurosci* **8**, 2,928-2,937.

Gibbs CH, Mahan PE, Mauderli A, Lundeen HC, Walsh EK (1986) Limits of human bite strength. *J Prosthet Dent* **56**, 226-229.

Goldberg LJ, Derfler B (1977) Relationship among recruitment order, spike amplitude, and twitch tension of single motor units in human masseter muscle. *J Neurophysiol* **40**, 879-890.

Goldspink G (1976) The adaptation of muscle to a new functional length. In: Anderson DJ, Matthews B (eds.) *Mastication*. John Wright and Sons, Bristol, UK.

Gordon AM, Huxley AF, Julian FJ (1966) The variation in isometric tension with sarcomere length in vertebrate muscle fibres. *J Physiol* **184**, 170-192.

Graf H, Grassl H, Aebfrhard HJ (1974) A method for measurement of occlusal forces in three directions. *Helv Odont Acta* **18**, 7-11.

Grant PG (1973) Lateral pterygoid: two muscles? *Am J Anat* **138**, 1-10.

Gray's Anatomy (1980) Williams PL, Warwick R (eds.) 36th edition. Churchill Livingstone, Edinburgh. *pp*. 529-536.

Grant PG (1973) Lateral pterygoid: two muscles? *Am J Anat* **138**, 1-10.

Greaves WS (1978) The jaw lever system in ungulates. A new model. *J Zool London* **184**, 271-285.

Greene CS, Laskin DM (1972) Splint therapy for the myofascial pain-dysfunction (MPD) syndrome: A comparative study. *J AM Dent Assoc* **84**, 624-628.

Greenfield BE, Wyke B (1966) Reflex innervation of the temporomandibular joint. *Nature* **211**, 940-941.

Griffin CJ, Munro RR (1969) Electromyography of the jaw closing muscles in the open-close-clench cycle in man. *Arch Oral Biol* **14**, 141-149.

Guelinckx P, Dechow PC, Vanrusselt R, Carlson DS (1986) Adaptations in the temporalis muscles of rabbits after masseter muscle removal. *J Dent Res* **65**, 1,294-1,299.

Hagberg C, Agerberg G, Harberg M (1985) Regression analysis of electromyographic activity of masticatory muscles versus bite force. *Scand J Dent Res* **93**, 396-402.

Hagberg C (1986*a*) The amplitude distribution of electromyographic activity of masticatory muscles during unilateral chewing. *J Oral Rehab* **13**, 567-574.

Hagberg C (1986*b*) Electromyography and bite force studies of muscular function and dysfunction in masticatory muscles. *Swed Dent J (Suppl.)* **37**, 1-64.

Hagberg C (1987*a*) Assessments of bite force: a review. *J Craniomandibular Disorders* **1**, 162-169.

Hagberg C (1987*b*) EMG versus force relationship in painful masseter muscles before and after intramuscular anesthetics and saline injections. *Scand J Dent Res* **95**, 259-265.

Hagberg C, Hagberg M (1989) Muscular tenderness evaluated by surface EMG frequency analysis of isometric contractions. *Scand J Dent Res* **97**, 368-374.

Hannam AG, Matthews B, Yemm R (1969) Changes in the activity of the masseter muscle following tooth contact in man. *Arch Oral Biol* **14**, 1,401-1,406.

Hannam AG (1969*a*) The response of periodontal mechanoreceptors in the dog to controlled loading of the teeth. *Arch Oral Biol* **14**, 781-791.

Hannam AG, Matthews B, Yemm R (1970) Receptors involved in the response of the masseter muscle to tooth contact in man. *Arch Oral Biol* **15**, 17-24.

Hannam AG (1976) Periodontal Mechanoreceptors. In Anderson DJ, Matthews B (eds). *Mastication*. John Wright and Sons Ltd. Bristol, UK. *pp*. 30-32.

Haraldson T, Carlsson GE, Dahlström L, Jansson T (1985) Relationship between myoelectric activity in masticatory muscles and bite force. *Scand J Dent Res* **93**, 539-545.

Harrison PJ (1983) The relationship between the distribution of motor unit mechanical properties and the forces due to recruitment and to rate coding for the generation of muscle force. *Brain Res* **264**, 311-315.

Hasan Z (1986) Optimized movement trajectories and joint stiffness in unperturbed, inertially loaded movements. *Biol Cybern* **53**, 373-382.

Helkimo E (1974) Studies on function and dysfunction of the masticatory system. II. Index for anamnestic and clinical dysfunction and occlusal state. *Swed Dent J* **67**, 101-121.

Helkimo E, Carlsson GE, Carmeli Y (1975) Bite force in patients with functional disturbances of the masticatory system. *J Oral Rehab* **2**, 397-406.

Helkimo E, Carlsson GE, Helkimo M (1977) Bite force and state of dentition. *Acta Odontol Scand* **35**, 297-303.

Helkimo E, Ingervall B (1978) Bite force and functional state of the masticatory system in young men. *Swed Dent J* **2**, 167-175.

Helle A, Tulensalo T, Ranta R (1983) Maximum bite force values of children in different age groups. *Proc Finn Dent Soc*. **79**, 151-154.

Hellsing G (1980) On the regulation of interincisor bite force in man. *J Oral Rehab* **7**, 403-411.

Hellsing G, Klineberg I (1983) The masseter muscle: the silent period and its clinical implications. *J Prosthet Dent* **49**, 106-112.

Hellsing G (1984) Functional adaptation to changes in vertical dimension. *J Prosthet Dent* **52**, 867-870.

Hellsing G (1988) Human jaw muscle motor behaviour. II. Reflex and receptor mechanisms. *Swed Dent J* **12**, 47-56.

Henneman E (1957) Relations between size of neurons and their susceptibility to discharge. *Science* **126**, 1,345-1,346.

Henneman E, Olson (1965) Relation between structure and function in the design of skeletal muscles. *J Neurophysiol* **28**, 581-598.

Henneman E, Somjen EG, Carpenter DO (1965) Functional significance of cell size in spinal motoneurons. *J Neurophysiol* **28**, 560-580.

Henneman E (1980) Skeletal muscle. The servant of the nervous system. In: Mountcastle VB (ed.) *Medical Physiology*, 14th ed. CV Mosby, St. Louis, *pp*. 674-702.

Hernandez CJ, Bodine RL (1969) Mastication strength with implant dentures as compared with soft-tissue-borne dentures. *J Prosthet Dent* **22**, 479-486.

Herring SW (1976) The dynamics of mastication in pigs. *Arch Oral Biol* **21**, 473-480.

Herring SW, Grimm AF, Grimm BR (1979) Functional heterogeneity in a multipinnate muscle. *Am J Anat* **154**, 563-579.

Herring SW (1980) Functional design of cranial muscles: Comparative and physiological studies in pigs. *Am Zool* **20**, 283-293.

Herring SW, Grimm AF, Grimm BR (1984) Regulation of sarcomere number in skeletal muscle: a comparison of hypotheses. *Muscle & Nerve* **7**, 161-173.

Herring SW, Wineski LE, Anapol FC (1989) Neural organization of the masseter muscle in the pig. *J Comp Neurol* **280**, 567-576.

Herring SW (1991) Functional properties of the feeding musculature. In: Bels VL, Chardon M, Vandewalle P (eds) *Biomechanics of feeding in vertebrates*, In series *Advances in Comparative and Environmental Physiology*. Springer-Verlag:Berlin.

Herring SW, Mucci RJ (1991) *In vivo* strain in cranial sutures: the zygomatic arch. *J Morphol* **207**, 225-239.

Hiiemae KM, Kay RF (1973) Evolutionary trends in dynamics of primate mastication. In: Zingeser MR (ed.) *Craniofacial Biology of Primates*. Karger, New York. *pp*. 28-64.

Hogan N, Flash T (1987) Moving gracefully: quantitative theories of motor coordination. *Trends in Neurosci* **10**, 170-174.

Holmgren K, Sheikholeslam A, Riise C (1985) An electromyographic study of the immediate effect of an occlusal splint on the postural activity of the anterior temporal and masseter muscle in different body positions with and without visual input. *J Oral Rehab* **12**, 483-490.

Holmgren K, Sheikholeslam A, Riise C, Kopp S (1990) The effects of an occlusal splint on the electromyographic activities of the temporal and masseter muscles during maximal clenching in patients with a habit of nocturnal bruxism and signs and symptoms of craniomandibular disorders. *J Oral Rehab* **17**, 447-459.

Howell JH, Chila AG, Ford G, David D, Gates T (1986) An electromyographic study of elbow motion during post-exercise muscle soreness. *J Appl Physiol* **58**, 1,713-1,718.

Hutchins MO, Skjonsby HS (1990) Microtrauma to rat superficial masseter muscles following lengthening contractions. *J Dent Res* **69**, 1,580-1,585.

Hylander WL (1978) Incisal bite force direction in humans and the functional significance of mammalian mandibular translation. *Am J Phys Anthropol* **48**, 1-8.

Hylander WL, Johnson KR (1985) Temporalis and masseter muscle function during incision in Macaques and humans. *Int J Primatol* **6**, 289-322.

Hylander WL, Johnson KR (1989) The relationship between masseter force and masseter electromyogram during mastication in the monkey *Macaca fascicularis*. *Arch Oral Biol* **34**, 713-722.

Ingervall B, Thilander B (1974) Relation between facial morphology and activity of the masticatory muscles. *J Oral Rehab* **1**, 131-147.

Ingervall B, Helkimo E (1978) Masticatory muscle and facial morphology in man. *Arch Oral Biol* **23**, 203-206.

Ingervall B, Bitsanis E (1987) A pilot study of the effect of masticatory muscle training on facial growth in long-face children. *Eur J Orthod* **9**, 15-23.

Inman VT, De Saunders JB, Feinstein B, Wright EW Jr. (1952) Relation of human electromyogram to muscular tension. *Electroenceph Clin Neurophysiol* **4**, 187-194.

Isacsson G, Isberg A, Persson A (1988) Loss of directional orientation control of lower jaw movements in persons with internal derangement of the temporomandibular joint. *Oral Surg Oral Med Oral Pathol* **66**, 8-12.

Jenkins GE (1978) *The Physiology and Biochemistry of the Mouth.* 4th edition, Blackwell Scientific Publications, Oxford, England.

Jones DA, Newham DJ, Clarkson PM (1987) Skeletal muscle stiffness and pain following eccentric exercise of the elbow flexors. *Pain* **30**, 233-242.

Jones DA, Round JM (1990) Muscular pain. In: *Skeletal muscle in health and disease - A textbook of muscle physiology*. Manchester University Press, Manchester, USA. *pp.* 175-188.

Kalaska JF, Cohen DAD, Hyde ML, Prud'homme M (1989) A comparison of movement direction-related versus load direction-related activity in primate motor cortex, using a two-dimensional reaching task. *J Neurosci* **9**, 2,080-2,102.

Kawazoe Y, Kotani H, Hamada T (1979) Relation between integrated electromyographic activity and biting force during voluntary isometric contraction in human masticatory muscles. *J Dent Res* **58**, 1,440-1,449.

Kawazoe Y, Kotani H, Hamada T, Yamada S (1980) Effects of occlusal splint on the electromyographic activities of masseter muscles during maximum clenching in patients with myofacial pain dysfunction syndrome. *J Prosthet Dent* **43**, 578-580.

Kistler Instrument Co. *Technical data #* 6.9251.

Klineberg I, Greenfield BE, Wyke BD (1971) Afferent discharges from temporomandibular articular mechanoreceptors. *Arch Oral Biol* **16**, 1,463-1,475.

Koolstra JH, van Eijden TMGJ, Weijs WA, Naeije M (1988) A three-dimensional mathematical model of the human masticatory system predicting maximum possible bite forces. *J Biomech* **21**, 563-576.

Kroon GW, Naeije M (1992) Electromyographic evidence of local muscle fatigue in a subgroup of patients with myogenous craniomandibular disorders. *Arch Oral Biol* **37**, 215-218.

Kuroda V, Klissouras V, Milsum JH (1970) Electrical and mechanical activities and fatigue in human isometric contraction. *J Appl Physiol* **29**, 535-548.

Larsson L-E, Thilander B (1964) Mandibular positioning: the effect of pressure on the joint capsule. *Acta Neurol Scand* **40**, 131-143.

Laskin DM (1969) Etiology of the pain-dysfunction syndrome. *J Am Dent Assoc* **79**, 141-153.

Laskin DM, Block L (1986) Diagnosis and treatment of myofascial pain dysfunction syndrome. *J Prosthet Dent* **56**, 76-84.

Laurell L (1985) Occlusal forces and chewing ability in dentitions with cross-arch bridges (thesis). *Swed Dent J* (suppl 26) 1985.

Laurell L, Lundgren D (1984) A standardized programme for studying the occlusal force pattern during chewing and biting in prosthetically restored dentitions. *J Oral Rehab* **11**, 39-44.

Lavigne G, Kim JS, Valiquette C, Lund JP (1987) Evidence that periodontal pressoreceptors provide positive feedback to jaw closing muscles during mastication. *J Neurophysiol* **58**, 342-358.

Leff A (1966) Gnathodynamics of four mandibular positions. *J Prosthet Dent* **16**, 844-847.

Lenman JAR (1959*a*) A clinical and experimental study of the effects of exercise on motor weakness in neurological diseases. *J Neurol, Neurosurg and Psychiat* **22**, 182-194.

Lenman JAR (1959*b*) Quantitative electromyographic changes associated with muscular weakness. *J Neurol, Neurosurg and Psychiat* **22**, 306-314.

Lenman JAR, Ferguson IT (1988) Integration and analysis of the electromyogram and the study of reflexes. In: Walton J (ed) *Disorders of Voluntary Muscle.* 5th ed. Churchil-Livingstone, Edinburgh, Scotland. *pp.* 1,110-1,134.

Lewis GR, Yemm R (1983) Measurement of the ability to control jaw muscle forces in man. *J Dent Res* **62**, 821-824.

Libkind MS (1972*a*) Modelling of interference bioelectrical activity; IV. *Biophysics* **17**, 124-130.

Libkind MS (1972*b*) Modelling of interference bioelectrical activity; V. *Biophysics* **17**, 130-137.

Lindauer SJ, Gay T, Rendell J (1991) Electromyographic-force characteristics in the assessment of oral function. *J Dent Res* **70**, 1,417-1,421.

Linderholm H, Wennstrom A (1970) Isometric bite force and its relation to general muscle force and body build. *Acta Odontol Scand* **28**, 679-689.

Linderholm H, Lindqvist B, Ringqvist M, Wennstrom A (1971) Isometric bite force in children and its relation to body build and general muscle force. *Acta Odontol Scand* **29**, 563-568.

Lindqvist B, Ringqvist M (1973) Bite force in children with bruxism. *Acta Odontol Scand* **31**, 255-259.

Lippold OCJ (1952) The relation between integrated EMG action potentials in a human muscle and its isometric tension. *J Physiol (Lond)* **117**, 492-499.

Lofberg PG (1960) Metodstudie for matning av tuggtryck. *Svensk Tandlak T* **53**, 325-335.

Lous I, Sheikoleslam A, Moller E (1970) Postural activity in subjects with functional disorders of the chewing apparatus. *Scand J Dent Res* **78**, 404-410.

Lund JP, Lamarre Y (1973) The importance of positive feedback from periodontal pressoreceptors during voluntary isometric contraction of jaw closing muscles in man. *J Biol Bucc* **1**, 345-351.

Lund JP, Richmond FJR, Touloumis C, Patry Y, Lammarre Y (1978) The distribution of Golgi tendon organs and muscle spindles in masseter and temporalis muscles in the cat. *Neurosci* **3**, 259-270.

Lund JP, Widmer CG (1989) An evaluation of the use of surface electromyography in the diagnosis, documentation, and treatment of dental patients. *J Craniomand Disorders Facial & Oral Pain* **3**, 125-137.

Lund JP, Widmer CG, Schwartz G (1989) What is the link between myofascial pain and dysfunction? In: van Steenberghe D, De Latt A (eds.) *EMG of jaw reflexes in man*. pp. 427-444.

Lundgren D, Laurell L (1984) Occlusal forces in prosthetically restored dentitions: a methodological study. *J Oral Rehab* **11**, 29-37.

Lyon MF, Baxendale RH (1990) A preliminary electromyographic study of bite force and jaw-closing muscle fatigue in human subjects with advanced tooth wear. *J Oral Rehab* **17**, 311-318.

MacDonald JWC, Hannam AG (1984*a*) Relationship between occlusal contacts and jaw-closing muscle activity during tooth clenching: Part I. *J Prosthet Dent* **52**, 718-728.

MacDonald JWC, Hannam AG (1984*b*) Relationship between occlusal contacts and jaw closing muscle activity during tooth clenching: Part II. *J Prosthet Dent* **52**, 862-867.

MacKennna BR, Turker KS (1978) Twitch tension in the jaw muscles of the cat at various degrees of mouth openings. *Arch Oral Biol* **23**, 917-920.

Mackenna BR, Turker KS (1983) Jaw separation and maximum incising force. *J Prosthet Dent* **49**, 726-730.

Majewski RF, Gale EN (1984) Electromyographic activity of anterior temporal area pain patients and non-pain subjects. *J Dent Res* **63**, 1,228-1,231.

Major PW (1988) Splint therapy to increase TMJ joint space. MSc Thesis. University of Alberta.

Manns A, Spreng M (1977) EMG amplitude and frequency at different muscular elongations under constant masticatory force or EMG activity. *Acta Physiol Lat Am* **27**, 259-262.

Manns A, Miralles R, Palazzi C (1979) EMG, bite force, and elongation of the masseter muscle under isometric voluntary contractions and variations of vertical dimensions. *J Prosthet Dent* **42**, 674-682.

Manns A, Miralles R, Cumsille F (1985) Influence of vertical dimension on masseter muscle electromyographic activity in patients with mandibular dysfunction. *J Prosthet Dent* **53**, 243-247.

Manns A, Miralles R, Valdivia J, Bull R (1989) Influence of variation in anteroposterior occlusal contacts on electromyographic activity. *J Prosthet Dent* **61**, 617-623.

Mansour RM, Reynik RJ (1975*a*) *In vivo* occlusal forces and moments: I. Forces measured in terminal hinge position and associated moments. *J Dent Res* **54**, 114-120.

Mansour RM, Reynik RJ (1975*b*) *In vivo* occlusal forces and moments: II. Mathematical analysis and recommendations for instrumentation specifications. *J Dent Res* **54**, 121-124.

Mao J, Stein RB, Osborn JW (1992*a*) The size and distribution of fibre types in mammalian jaw muscles; a review. *J Craniomand Disorders Facial Oral Pain* **6**, 192-201.

Mao J, Stein RB, Osborn JW (1992*b*) Fatigue in human jaw muscles; a review. *J Craniomand Fac Oral Pain* (in press).

Mao J, Stein RB, Osborn JW (1992) Synergistic muscle compensation during fatigue. Abstract submitted to 1992 Society for Neuroscience annual conference.

Marklund G, Molin C (1972) Horizontal isometric muscle forces of the mandible, A comparative study of subjects with and without manifest mandibular pain dysfunction syndrome. *Acta Odontol Scand* **39**, 97-115.

Martin PR, Matthews AM (1978) Tension headaches: psychophysiological investigations and treatment. *J Psychosomat Res* **22**, 389-399.

Matthews B, Yemm R (1970) A silent period in the masseter electromyogram following tooth contact in subjects wearing full dentures. *Arch Oral Biol* **15**, 531-535.

McMillan AS, Sasaki K, Hannam AG (1990) The estimation of motor unit twitch tensions in the human masseter muscle by spike-triggered averaging. *Muscle & Nerve* **13**, 697-703.

McNamara JA Jr. (1974) An electromyographic study of mastication in the Rhesus monkey *(Macaca Mulatta)*. *Arch Oral Biol* **19**, 821-823.

Mercuri LG, Olson RE, Laskin DM (1979) The specificity of response to experimental stress in patients with myofascial pain-dysfunction syndrome. *J Dent Res* **58**, 1,866-1,871.

Mills JRE (1973) Evolution of mastication in primates. In: Zingeser MR (ed.) *Craniofacial Biology of Primates*. Karger, New York, USA. *pp*. 65-81.

Milner-Brown HS, Stein RB, Yemm R (1973*a*) The contractile properties of human motor units during voluntary isometric contractions. *J Physiol* **228**, 285-306.

Milner-Brown HS, Stein RB, Yemm R (1973*b*) The orderly recruitment of human motor units during voluntary isometric contractions. *J Physiol* **230**, 359-370.

Milner-Brown HS, Stein RB (1975) The relation between the surface electromyogram and muscular force. *J Physiol* **246**, 549-569.

Molin C (1972) Vertical isometric muscle forces of the mandible. A comparative study of subjects with and without manifest mandibular pain dysfunction syndrome. *Acta Odontol Scand* **30**, 485-499.

Moller E (1966) The chewing apparatus. An electromyographic study of the action of the muscles of mastication and its correlation to facial morphology. (PhD thesis) *Acta Physiol Scan* **69**, (supp) 280, 1-229.

Moller E, Sheikholeslam A, Lous I (1971) Deliberate relaxation of the temporal and masseter muscles in subjects with functional disorders of the chewing apparatus. *Scand J Dent Res* **79**, 478-482.

Moller E (1974) Action of the muscles of mastication. In: *Frontiers of Oral Physiology*. Karger, Basel. pp. 121-158.

Moller E (1975) Quantitative features of masticatory muscle activity. In: Rowe NH (ed) *Occlusion: Research in Form and Function*. Univ. of Michigan Press, Ann Arbor, USA. *pp*. 109-118.

Moller E (1985) Muscle hyperactivity leads to pain and dysfunction. In: Klineberg I, Sessle B (eds.) *Oro-facial pain and Neuromuscular Dysfunction: Mechanisms and Clinical Correlates*. Advances in the Biosciences. Vol. 52. Proceedings of the Symposium sponsored by the International Commission on Oral Physiology of the International Union of Physiological Sciences, the Neuroscience Group of the International Association for Dental Research and the Australian Prosthodontic Society, held at the University of Sydney, Australia, 5th and 6th August 1983. Pergamon Press, Oxford, England.

Moore AP (1967) Synthesized EMG waves and their implications. *Am J Phys Med* **46**, 1,302-1,316.

Naeije M, Hansson TL (1986) Electromyographic screening of myogenous and arthrogenous TMJ dysfunction patients. *J Oral Rehab* **13**, 433-441.

Naeije M, McCarroll RS, Weijs WA (1989) Electromyographic activity of the human masticatory muscles during submaximal clenching in the inter-cuspal position. *J Oral Rehab* **16**, 63-70.

Naeije M, Hansson TL (1991) Short-term effect of the stabilization appliance on masticatory muscle activity in myogenous craniomandibular disorder patients. *J Craniomand Disorders Facial Oral Pain* **5**, 245-250.

Neill DJ, Kydd WL, Nairn RI, Wilson J (1989) Functional loading of the dentition during mastication. *J Prosthet Dent* **62**, 218-228.

Nielsen IL, McNeill C, Danzig W, Goldman S, Levy J, Miller AJ (1990) Adaptation of craniofacial muscles in subjects with craniomandibular disorders. *Am J Orthod Dentofac Orthop* **97**, 20-34.

Nordstrom SH, Yemm R (1972) Sarcomere length in the masseter muscle of the rat. *Arch Oral Biol* **17**, 895-902.

Nordstrom SH, Yemm R (1974) The relationship between jaw position and isometric active tension produced by direct stimulation of the rat masseter muscle. *Arch Oral Biol* **19**, 353-359.

Oguztoreli MN, Stein RB (1990) Optimal task performance of antagonistic muscles. *Biol Cybergn* **64**, 87-94.

Olsson KA, Lund JP, Valiquette C, Veilleux D (1988) Activity during mastication of periodontal mechanosensitive neurons of the trigeminal subnucleus oralis of the rabbit. *J Neurophysiol* **59**, 341-357.

Orchardson R, MacFarlane SH (1980) The effects of local periodontal aneaesthesia on the maximum biting force achieved by human subjects. *Arch Oral Biol* **25**, 799-804.

O'Rourke JT (1949) Significance of tests of biting strength. *J Am Dent Assoc* **38**, 627-633.

Osborn JW (1982) The helicoidal plane of occlusion. *Am J Phys Anthropol* **57**, 273-281.

Osborn JW, Baragar FA (1985) Predicted pattern of human muscle activity during clenching derived from a computer assisted model: Symmetric vertical bite forces. *J Biomech* **18**, 599-612.

Osborn JW, Baragar FA, Grey P (1986) The functional advantage of proclined incisors in man. In: Russel DE, Santoro J-P, Sigogneau-Russell D (eds.) *Teeth Revisited: Proceedings of VII Int. Symp. on Dental Morphology. Mem Mus Natn Hist Nat, Paris, (serie C)* **53**, 445-458.

Osborn JW (1987) Relationship between the mandibular condyle and the occlusal plane during hominid evolution: some of its effects on jaw mechanics. *Am J Phys Anthropol* **73**, 193-207.

Osborn JW (1989) The temporomandibular ligament and the articular eminence as constraints during jaw opening. *J Oral Rehab* **16**, 323-333.

Osborn JW (1992) A model to describe how ligaments may control symmetrical jaw opening movements in man. *J Oral Rehab* (in press).

Osborn JW, Baragar AF (1992) Predicted and observed shapes of human mandibular condyles. *J Biomech* (in press).

Osborn JW, Mao J (1992) A thin bite force transducer with 3 dimensional capabilities reveals a change in bite force direction during jaw muscle endurance test. *Archs Oral Biol* (in press).

Osborn JW: The orientation of the masseter muscle and the curve of Spee in relation to crushing forces on molar teeth. *Am J Phys Anthropol* (in press).

Perry CC, Lissner HR (1962) *The Strain Gage Primer.* (2nd. ed.) pp. 268-269. McGraw-Hill Book Co. New York, USA.

Proffit WR, Fields HW (1983) Occlusal forces in normal- and long-face children. *J Dent Res* **62**, 571-574.

Proffit WR, Fields HW, Nixon WL (1983) Occlusal forces in normal- and long-face adults. *J Dent Res* **62**, 566-571.

Pruim GJ, Ten Bosch JJ, De Jongh HJ (1978) Jaw muscle EMG-activity and static loading of the mandible. *J Biomech* **11**, 389-395.

Pruim GJ (1979) Asymmetries of bilateral static bite forces in different locations on the human mandible. *J Dent Res* **58**, 1,685-1,687.

Rack PMH, Westbury DR (1969) The effects of length and stimulus rate on tension in the isometric cat soleus muscle. *J Physiol (Lond)*, **204**, 443-460.

Rasmussen P (1965) *Facial Pain*. Munksgaard, Copenhagen. p. 15

Ringqvist M (1973*a*) Isometric bite force and its relation to dimensions of facial skeleton. *Acta Odont Scand* **31**, 35-42.

Ringqvist M (1973*b*) Histochemical enzyme profiles of fibres in human masseter muscles with special regard to fibres with intermediate myofibrillar ATPase reaction. *J Neurol Sci* **18**, 133-141.

Rosenbaum DA (1980) Human movement initiation: Specification of arm, direction, and extent. *J Exp Psychol: General* **109**, 444-474.

Rosenbaum DA (1990) *Human Motor Control*. Part I preliminaries. Academic Press, Inc., San Diego, USA.

Rowlett AE (1932) The gnathodynamometer and its use in dentistry. *Proc R Soc Med* **26**, 463-471.

Rugh JD, Solberg WK (1972) The measurement of human oral forces. *Behav Res Meth & Instru* **4**, 125-128.

Salmons S, Henriksson J (1981) The adaptive response of skeletal muscle to increased use. *Muscle & Nerve* **4**, 94-105.

Sasaki K, Hannam AG, Wood WW (1989) Relationship between the size, position, and angulation of human jaw muscles and unilateral first molar bite force. *J Dent Res* **68**, 499-503.

Schroeder H, Lehrbuck Der A (1927) Technixchen Zahuheilkunde, Vol. I, part II. Berlin: Herm. Mensser. *pp.*, 249-309.

Schumacher GH (1961) Funktionelle Morphologie der Kaumuskulatur. VEB Gustav Fischer Verlag, Jena.

Sessle BJ, Schmitt A (1972) Effects of controlled tooth stimulation on jaw muscle activity in man. *Arch Oral Biol* **17**, 1,597-1,607.

Sessle BJ, Woodside DG, Bourque P, Gurza S, Powell G, Voudouris J, Metaxas A, Altuna G (1990) Effect of functional appliances on jaw muscle activity. *Am J Orthod Dentofacial Orthop* **98**, 222-230.

Sheikholeslam A, Moller E, Lous I (1980) Pain, tenderness and strength of human mandibular elevators. *Scand J Dent Res* **88**, 60-66.

Sheikholeslam A, Moller E, Lous I (1982) Postural and maximal activity in elevators of the mandible before and after treatment of functional disorders. *Scand J Dent Res* **90**, 37-46.

Sheikholeslam A, Holmgren K, Riise C (1986) A clinical and electromyographic study of the long-term effects of an occlusal splint on the temporal and masseter muscles in patients with functional disorders and nocturnal bruxism. *J Oral Rehab* **13**, 137-145.

Sherman R (1985) Relationship between jaw pain and jaw muscle contraction level: underlying factors and treatment effectiveness. *J Prosthet Dent* **54**, 114-118.

Sicher H, DuBrul EL (1975) *Oral Anatomy*. CV Mosby, Saint Louis, USA.

Smith DM, McClachlan KR, McCall WD (1986) A numerical model of temporomandibular joint loading. *J Dent Res* **65**, 1,046-1,052.

Soechting JF, Terzuolo CA (1990) Sensorimotor transformations and kinematics of arm movements in three-dimensional space. In Jeannerod M (ed.) *Attention and Performance XIII*. Hillsdale NJ: Erlbaum. *pp. 479-494*.

Solberg WK, Clark GT, Rugh JD (1975) Nocturnal electromyographic evaluation of bruxism patients undergoing short term splint therapy. *J Oral Rehab* **2**, 215-223.

Stegenga B, Broekhuijsen ML, van Willingen JD (1990) Clinical significance of bite force reproduction ability. *J Craniomand Disorders Facial Oral Pain* **4**, 6-16.

Stein RB, Milner-Brown HS (1973) Contractile and electrical properties of normal and modified human motor units. In: *Control of Posture and Locomotion*. Plenum Press, New York, USA. *pp*. 73-86.

Stein RB (1974) The peripheral control of movement. *Physiol Rev* **54**, 215-243.

Stein RB (1980) Muscular contraction. In *Nerve and Muscle - Membranes, Cells and Systems*. Plenum Press, New York, USA. *pp*. 117-47.

Stein RB (1982) What muscle variable(s) does the nervous system control in limb movements? *The Behav & Brain Sci* **5**, 535-578.

Stephens JA, Taylor A (1972) Fatigue of maintained voluntary muscle contraction in man. *J Physiol (Lond)* **220**, 1-18.

Stohler CS, Ash MM Jr. (1984) Silent period in jaw elevator muscle activity during mastication. *J Prosthet Dent* **52**, 729-735.

Stohler CS (1986) A comparative electromyographic and kinesiographic study of deliberate and habitual mastication in man. *Arch Oral Biol* **31**, 669-678.

Stohler CS, Yamada Y, Ash MM (1988) The effects of pain from the mandibular joint and muscles on masticatory motor behavior in man. *Arch Oral Biol* **33**, 175-182.

Storey AT (1962) Physiology of a changing vertical dimension. *J Prosthet Dent* **12**, 912-921.

Storey AT (1992) Neurophysiology. In: Sarnat BG, Laskin DM (eds.) *The Temporomandibular Joint: a Biological Basis for Clinical Practice*. Saunders Co., Philadelphia, USA. *pp*. 108-123.

Talley, Murphy GJ, Smith SD, Baylin MA, Haden JL (1990) Standards for the history, examination, diagnosis, and treatment of temporomandibular disorders (TMD): a position paper. *J Craniomand Practice* **8**, 60-77.

Tax AAM, Denier van der Gon JJ, Erkelens CJ (1989) Differences in the activation of elbow flexor muscles in the control of slow isotonic movements and isometric contractions. *Exp Brain Res* **76**, 55-63.

Tax AAM, Denier van der Gon JJ, Gielen CCAM, Erkelens CJ (1990*a*) Differences in central control of m. biceps brachii in movement tasks and force tasks. *Exp Brain Res* **81**, 138-142.

Tax AAM, Denier van der Gon JJ, Erkelens CJ (1990*b*) Differences in coordination of elbow flexor muscles in force tasks and in movement tasks. *Exp Brain Res* **81**, 567-572.

Teenier TJ, Throckmorton GS, Ellis III E (1991) Effects of local anesthesia on bite force generation and electromyographic activity. *J Oral Maxillofac Surg* **49**, 360-365.

Thexton AJ, Hiiemae KM (1975) The twitch tension characteristics of opossum jaw musculature. *Arch oral Biol* **20**, 743-748.

Tilley DE (1979) *Contemporary College Physics*. The Benjamin/Cummings Publishing Co. Inc., Menlo Park, USA. *pp*. 56-80.

Tonndorf ML, Sasaki K, Hannam AG (1989) Single-wire recording of regional activity in the human masseter muscle. *Brain Res Bulletin* **23**, 155-159.

Turker KS, Milles TS (1985) The effect of stimulus intensity and gape on electrically-evoked jaw reflexes in man. *Arch Oral Biol* **30**, 621-626.

Uno Y, Kawato M, Suzuki R (1989) Formation and control of optimal trajectory in human multijoint arm movement: minimum torque-change model. *Biol Cybergn* **61**, 89-101.

Van der Glas HW, Weytjens JLF, De Laat A, van Steenberghe D, Pardaens JL (1984) The influence of clenching level on the post-stimulus EMG complex, including silent periods, of the masseter muscle in man. *Arch Oral Biol* **29**, 51-58.

Van Eijden TMGJ, Koolstra JH, Brugman P, Weijs WA (1988*a*) A feedback method to determine the three-dimensional bite-force capabilities of the human masticatory system. *J Dent Res* **67**, 450-454.

Van Eijden TMGJ, Klok EM, Weijs WA, Koolstra JH (1988*b*) Mechanical capabilities of the human jaw muscles studied with a mathematical model. *Arch Oral Biol* **33**, 819-826.

Van Eijden TMGJ (1990) Jaw muscle activity in relation to the direction and point of application of bite force. *J Dent Res* **69**, 901-905.

Van Eijden TMGJ, Brugman P, Weijs WA, Oosting J (1990) Coactivation of jaw muscles: recruitment order and level as a function of bite force direction and magnitude. *J Biomech* **23**, 475-485.

Van Eijden TMGJ (1991) Three-dimensional analyses of human bite-force magnitude and moment. *Arch Oral Biol* **36**, 535-539.

Van Eijden TMGJ, Raadsheer MC (1992) Heterogeneity of fiber and sarcomere length in the human masseter muscle. *Anat Rec* **232**, 78-84.

Van Steenberghe D, De Vries JH (1978*a*) The development of a maximal clenching force between two antagonistic teeth. *J Periodont Res* **13**, 91-97.

Van Steenberghe D, De Vries JH (1978*b*) The influence of local anaesthesia and occlusal surface area on the forces developed during repetitive maximal clenching efforts. *J Periodont Res* **13**, 270-274.

Van Steenberghe D (1979) The structure and function of periodontal innervation: a review of the literature. *J Periodont Res* **14**, 91-97.

Vitti M, Junior BK (1970) Electromyographic analysis of the musculus temporalis (pars anterior) and its relationship to the musculus masseter (pars profunda). *Electromyography* **3**, 253-260.

Vitti M (1971) Electromyographic analysis of the musculus temporalis in basic movements of the jaw. *Electromyography* **4**, 389-403.

Vitti M, Basmajian JV (1977) Integrated actions of masticatory muscles: simultaneous EMG from eight intramuscular electrodes. *Anat Rec* **187**, 173-190.

Vredenbredt J, Rau G (1973) Surface electromyography in relation to force, muscle length and endurance. In: Desmedt JE (ed.) *New Development in Electromyography and Clinical Neurophysiology*. Karger, Basel. *pp*. 607-622.

Wastell DG, Devlin H (1987) The accelerative component of EMG in bite force development in man. *J Oral Rehab* **14**, 203-208.

Watanabe M, Hannam AG (1986) Bite force in three dimensions and associated jaw muscle activity. *J Dent Res* **65**, 804.

Waugh LM (1937) Dental observations among Eskimo. VII: Survey of mouth conditions, nutritional study and gnathodynamometer data, in most primitive and populous native villages in Alaska. *J Dent Res* **16**, 355-356.

Webster JG (1978) *Medical Instrumentation, Application and Design*. Houghton Mifflin Company, Boston MA, USA.

Weijs WA, Dantuma R (1981) Functional anatomy of the masticatory apparatus in the rabbit. *Netherlands J Zool* **31**, 99-147.

Weijs WA, van der Wielen-Drent TK (1983) The relationship between sarcomere length and activation pattern in the rabbit masseter muscle. *Arch Oral Biol* **28**, 307-315.

Widmalm S-E (1976) The silent period in the masseter muscle of patients with TMJ dysfunction. *Acta Odont Scand* **34**, 43-47.

Widmalm S-E, Ericsson SG (1982) Maximal bite force with centric and eccentric load. *J Oral Rehab* **9**, 445-450.

Widmalm S-E, Lillie JH, Ash MM Jr (1987) Anatomical and electromyographic studies of the lateral pterygoid muscle. *J Oral Rehab* **14**, 429-446.

Williams WN, LaPointe LL, Mahan PE, Cornell CE (1984*a*) The influence of TMJ and central incisor sensory impairment on bite force discrimination. *J Craniomand Practice* **2**, 119-124.

Williams WN, LaPointe LL, Mahan PE, Cornell CE (1984**b**) Vibratory stimulation of the masseter musculature and bite force discrimination. *J Craniomand Practice* **5**, 25-31.

Williams WN, Levin BDS, LaPointe LL (1985) Bite force discrimination by individuals with complete dentures. *J Prosthet Dent* **54**, 146-150.

Wood WW, Tobias DL (1984) EMG response to alteration of tooth contacts on occlusal splints during maximal clenching. *J Prosthet Dent* **51**, 394-396.

Wood WW (1986*a*) Medial pterygoid muscle activity during chewing and clenching in man. *J Prosthet Dent* **55**, 615-621.

Wood WW (1987) A review of masticatory muscle function. *J Prosthet Dent* **57**, 222-232.

Worner HK, Anderson MN (1944) Biting force measurements on children. *Aust J Dent* **48**, 1-12.

Yaffe A, Tal M, Ehrlich J (1991) Effect of occlusal bite-raising splint on electromyogram, motor unit histochemistry and myoneuronal dimensions in rats. *J Oral Rehab* **18**, 343-351.

Yemm R (1972*a*) The response of the masseter and temporal muscles following electrical stimulation of oral mucous membrane in man. *Arch Oral Biol* **17**, 23-33.

Yemm R (1972*b*) Reflex jaw-opening following electrical stimulation of oral mucous membrane in man. *Arch Oral Biol* **17**, 513-523.

Yemm R, Nordstrom SH (1974) Forces developed by tissue elasticity as a determinant of mandibular resting posture in the rat. *Arch Oral Biol* **19**, 347-351.

Yemm R (1977*a*) The orderly recruitment of motor units of the masseter and temporal muscles during voluntary isometric contraction in man. *J Physiol* **265**, 163-174.

Yemm R (1977*b*) The representation of motor-unit action-potentials on skin-surface electromyograms of the masseter and temporal muscles in man. *Arch Oral Biol* **22**, 201-205.

Yemm R (1985) A neurophysiological approach to the pathology and aetiology of temporomandibular dysfunction. *J Oral Rehab* **12**, 343-353.

Yurkstas A (1953) The effect of masticatory exercise of the maximum force tolerance of individual teeth. *J Dent Res* **32**, 322-327.

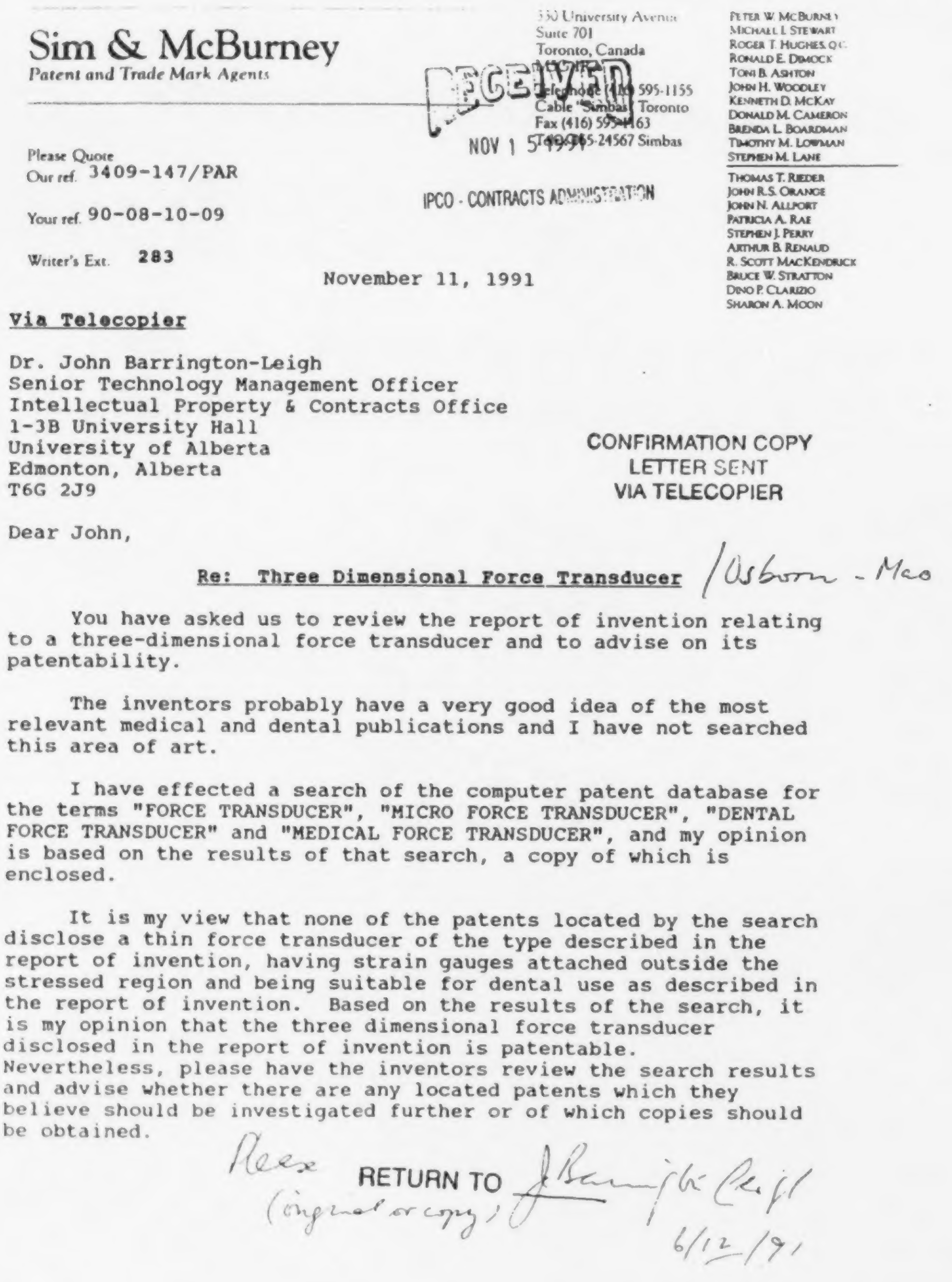
Yurkstas A, Curby WA (1953) Force analysis of prosthetic appliances during function. *J Prosthet Dent* **3**, 82-87.

Zarb GA, Speck JE (1979) The treatment of mandibular dysfunction. In: *Temporomandibular Joint*, Zarb GA, Carlsson GE (eds.), Munksgaard, Copenhagen. pp. 377-380.

Zulqarnain BJ, Furuya R, Hedegard B, Magnusson T (1989) The silent period in the masseter and the anterior temporalis muscles in adult patients with mild or moderate mandibular dysfunction symptoms. *J Oral Rehab* **16**, 127-137.

Zuniga NE, Simons DG (1969) Non-linear relationship between averaged electromyogram potential and muscle tension in normal subjects. *Arch Phys Med & Rehab* **50**, 613-627.

APPENDIX ITEM # 1
PENDING PATENT



Sim & McBurney
Patent and Trade Mark Agents

330 University Avenue
Suite 701
Toronto, Canada
[illegible]
Telephone (416) 595-1155
Cable "Simbas" Toronto
Fax (416) 595-1163
Telex 065-24567 Simbas

Peter W. McBurney
Michael I. Stewart
Roger T. Hughes, Q.C.
Ronald E. Dimock
Toni B. Ashton
John H. Woodley
Kenneth D. McKay
Donald M. Cameron
Brenda L. Boardman
Timothy M. Lowman
Stephen M. Lane

Thomas T. Rieder
John R.S. Orange
John N. Allport
Patricia A. Rae
Stephen J. Perry
Arthur B. Renaud
R. Scott MacKendrick
Bruce W. Stratton
Dino P. Clarizio
Sharon A. Moon

RECEIVED
NOV 15 1991
IPCO - CONTRACTS ADMINISTRATION

Please Quote
Our ref. 3409-147/PAR

Your ref. 90-08-10-09

Writer's Ext. **283**

November 11, 1991

Via Telecopier

Dr. John Barrington-Leigh
Senior Technology Management Officer
Intellectual Property & Contracts Office
1-3B University Hall
University of Alberta
Edmonton, Alberta
T6G 2J9

CONFIRMATION COPY
LETTER SENT
VIA TELECOPIER

Dear John,

Re: Three Dimensional Force Transducer /Osborn - Mao

You have asked us to review the report of invention relating to a three-dimensional force transducer and to advise on its patentability.

The inventors probably have a very good idea of the most relevant medical and dental publications and I have not searched this area of art.

I have effected a search of the computer patent database for the terms "FORCE TRANSDUCER", "MICRO FORCE TRANSDUCER", "DENTAL FORCE TRANSDUCER" and "MEDICAL FORCE TRANSDUCER", and my opinion is based on the results of that search, a copy of which is enclosed.

It is my view that none of the patents located by the search disclose a thin force transducer of the type described in the report of invention, having strain gauges attached outside the stressed region and being suitable for dental use as described in the report of invention. Based on the results of the search, it is my opinion that the three dimensional force transducer disclosed in the report of invention is patentable. Nevertheless, please have the inventors review the search results and advise whether there are any located patents which they believe should be investigated further or of which copies should be obtained.

Please RETURN TO J Barrington-Leigh
(original or copy!)
6/12/91

If you decide to go ahead with a patent application, I will require drawings of the transducer device of the invention and a detailed description of how it is constructed and used and how the results are interpreted. If the inventors have prepared a paper for publication in a scientific journal, this would be a good starting point. I will also need to be provided with a copy of the paper by Van Eijden referred to in the report of invention, as well as copies of any other relevant prior art known to the inventors.

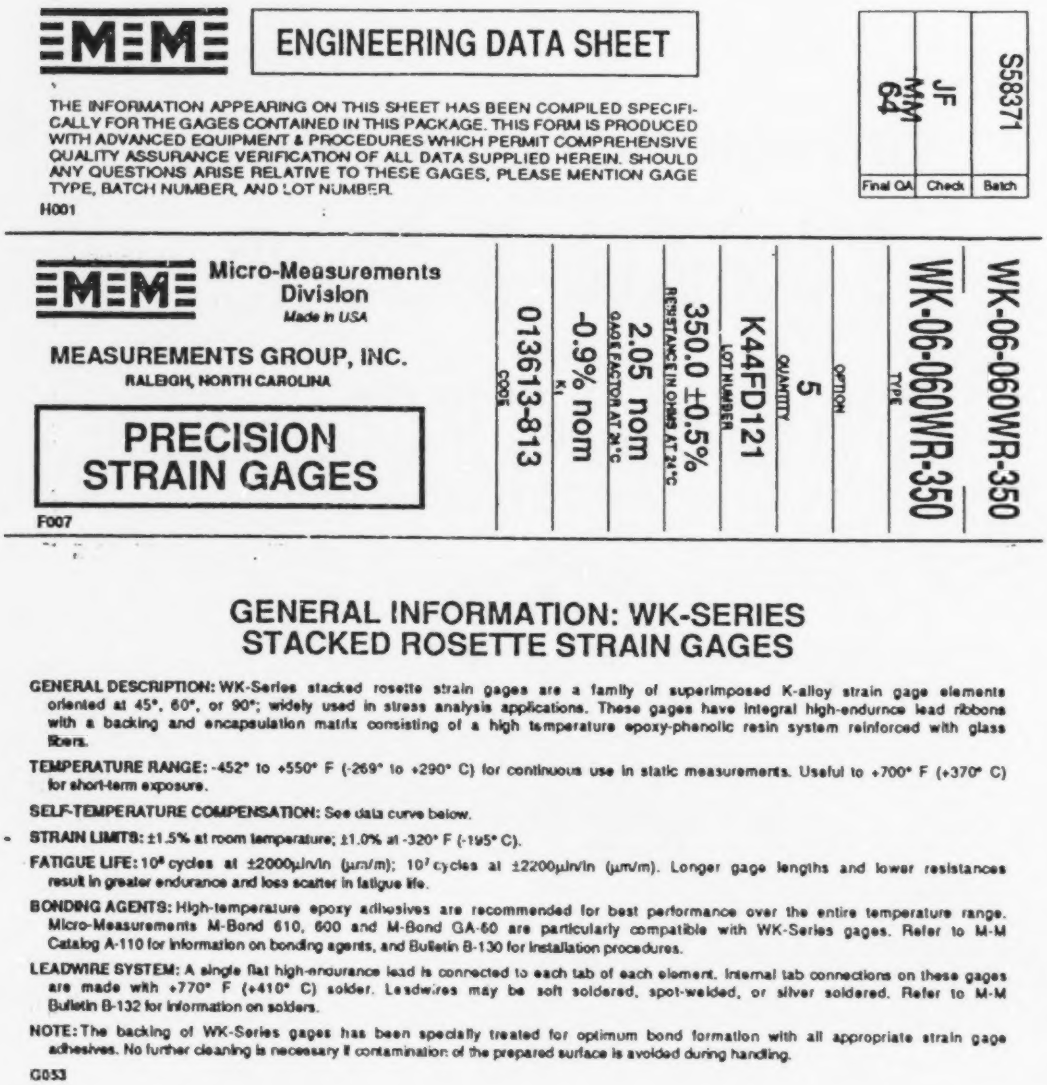
Yours truly,

SIM & McBURNEY

Per: Patricia Rae
Patricia A. Rae (Dr.)

PAR:ts

APPENDIX ITEM # 2
ENGINEERING DATA SHEET FOR THE STRAIN GAUGE ROSETTES



ENGINEERING DATA SHEET

THE INFORMATION APPEARING ON THIS SHEET HAS BEEN COMPILED SPECIFICALLY FOR THE GAGES CONTAINED IN THIS PACKAGE. THIS FORM IS PRODUCED WITH ADVANCED EQUIPMENT & PROCEDURES WHICH PERMIT COMPREHENSIVE QUALITY ASSURANCE VERIFICATION OF ALL DATA SUPPLIED HEREIN. SHOULD ANY QUESTIONS ARISE RELATIVE TO THESE GAGES, PLEASE MENTION GAGE TYPE, BATCH NUMBER, AND LOT NUMBER.

H001

Batch	Check	Final QA
S58371	JF MM	64

WK-06-060WR-350

TYPE: WK-06-060WR-350
OPTION:
QUANTITY: 5
LOT NUMBER: K44FD121
RESISTANCE IN OHMS AT 24°C: 350.0 ±0.5%
GAGE FACTOR AT 24°C: 2.05 nom
K1: -0.9% nom
CODE: 013613-813

Micro-Measurements Division
Made in USA

MEASUREMENTS GROUP, INC.
RALEIGH, NORTH CAROLINA

PRECISION STRAIN GAGES

F007

GENERAL INFORMATION: WK-SERIES STACKED ROSETTE STRAIN GAGES

GENERAL DESCRIPTION: WK-Series stacked rosette strain gages are a family of superimposed K-alloy strain gage elements oriented at 45°, 60°, or 90°; widely used in stress analysis applications. These gages have integral high-endurnce lead ribbons with a backing and encapsulation matrix consisting of a high temperature epoxy-phenolic resin system reinforced with glass fibers.

TEMPERATURE RANGE: -452° to +550° F (-269° to +290° C) for continuous use in static measurements. Useful to +700° F (+370° C) for short-term exposure.

SELF-TEMPERATURE COMPENSATION: See data curve below.

STRAIN LIMITS: ±1.5% at room temperature; ±1.0% at -320° F (-195° C).

FATIGUE LIFE: 10^8 cycles at ±2000μin/in (μm/m); 10^7 cycles at ±2200μin/in (μm/m). Longer gage lengths and lower resistances result in greater endurance and less scatter in fatigue life.

BONDING AGENTS: High-temperature epoxy adhesives are recommended for best performance over the entire temperature range. Micro-Measurements M-Bond 610, 600 and M-Bond GA-60 are particularly compatible with WK-Series gages. Refer to M-M Catalog A-110 for information on bonding agents, and Bulletin B-130 for installation procedures.

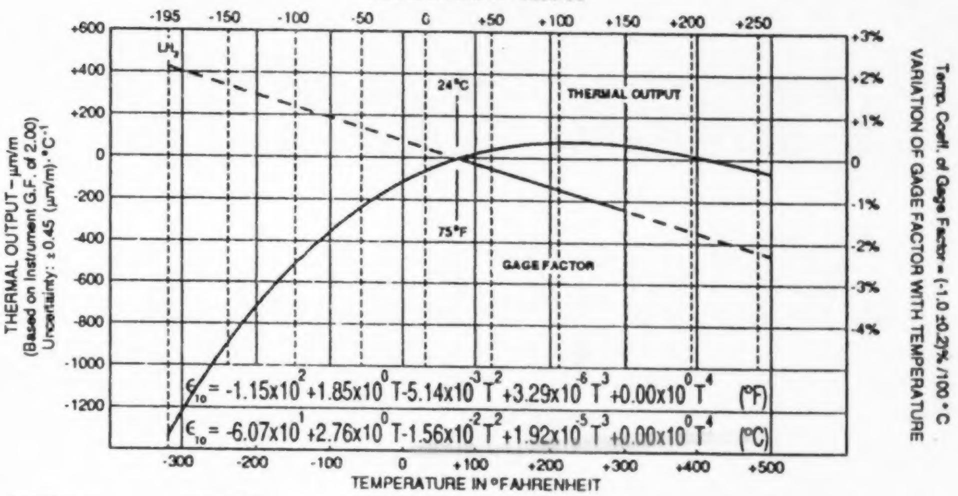
LEADWIRE SYSTEM: A single flat high-endurance lead is connected to each tab of each element. Internal tab connections on these gages are made with +770° F (+410° C) solder. Leadwires may be soft soldered, spot-welded, or silver soldered. Refer to M-M Bulletin B-132 for information on solders.

NOTE: The backing of WK-Series gages has been specially treated for optimum bond formation with all appropriate strain gage adhesives. No further cleaning is necessary if contamination of the prepared surface is avoided during handling.

G053

THERMAL OUTPUT

LOT NO. K44FD121



TESTED ON: 1018 STEEL TEST PATTERN: 250BG CODE: 993219 ENG. GU

TEST PROCEDURES USED BY MICRO-MEASUREMENTS

OPTICAL DEFECT ANALYSIS	**M-M Procedures and Standards**
GAGE RESISTANCE AT 24°C AND 50% RH	**M-M Procedure, Direct NBS Traceability on Resistance Standards**
GAGE FACTOR AT 24°C & 50% RH (UNIAXIAL STRESS FIELD - POISSON RATIO -0.285)	**ASTM E-251 (Constant Stress Cantilever Method)**
TEMPERATURE COEFFICIENT OF GAGE FACTOR	**ASTM E-251 (Step Deflection Method)**
THERMAL OUTPUT	**ASTM E-251 (Slow Heating Rate, Continuously Recorded)**
TRANSVERSE SENSITIVITY AT 24°C AND 50% RH	**ASTM E-251**
FATIGUE LIFE	**NAS 942 (Modified)**
STRAIN LIMITS	**NAS 942 (Modified)**
GAGE THICKNESS	**M-M Procedure**
CREEP AND DRIFT	**M-M Procedure (Similar to NAS 942 Method)**

NOTE: Gage resistance, gage factor, temperature coefficient of gage factor, thermal output, and transverse sensitivity testing and information presentation are in compliance with OIML International Recommendation NO. 62 "Performance characteristics of metallic resistance strain gages". Other tests are not included in I.R. NO. 62.

T001

APPENDIX ITEM # 3
STRAIN GAUGE INSTALLATION

1. Scratch the structural material

Sand paper #180, and then #320. Do not scratch too much; otherwise, it does not provide good adhesion.

2. Set the locations

Use a **ruler** to measure the width of the gauge and the location where the gauge will be installed. Mark the locations. Wash hands as before surgical operation.

3. Clean the surface

3 different solutions:
(1) **chlorothene SM**
(2) **metal conditioner**: 3 times, 20 *s* ea. Keep cleaning before it dries.
(3) **neutralizer**: apply neutralizer to larger area than the metal conditioner.

4. Protect the 2nd, 3rd gauge locations by tapes.

5. Install soldering points before putting the gauges on with tape.

6. Take a gauge out of the box and bag. Leave it on the box.

7. Tape it on the box. Then, take the whole thing off.

8. Put the gauge onto the location.

Fix the edges of the grid to the marked center.

9. Pull the tape off the surface with the gauge until 2 *mm* from the gage.

10. Catalyst 200 to the backup surface of the gauge. Let it dry for 1 min.

11. Apply M-bond (CA7 instant Adhesive) about one drop to the location where the gauge is intended to be. Put the gauge back. Apply constant force to it. Be aware that the gauge will be preloaded with this force. Therefore, apply the same amount of force to the 2nd, 3rd... gauges.

12. Leave it for 1 min. Then, peel the tape off very carefully in different directions. A gauge might be peeled off with the tape if it has been left bonded for too short a time. However, if it is left being bonded too long, there will be difficulty to take the tape off.

13. Use the spare time to do the 2nd gauge and to prepare the wires.

14. Soldering Put black insulating tape next to the soldering area to minimize thermal damage. Add M-Flux AR to the soldering area. Solder the wires to soldering areas. Don't let the naked wire touch the structural material. Leave the soldering point as small as possible.

15. Cleaning the soldering area with same solution (M-line Rosin Solvent - Flammable hazard toluene) in 3 different bottles (less and less contamination in the sequence of #1, 2, & 3) again and again. This procedure is for clearing off the metal due to soldering; otherwise, there will be a leakage from soldering joint to the structural material. Dry it with Klineex. Be careful with soldering points.

16. Fix the wires with Crazy Glue (or old M-Bond). Protect all other areas with a piece of paper while spraying accelerator (Tak Pak) to the bonding zone of the wire.

17. Stick numbers to gages.

18. Testing

(1) Gauge resistance. If it shows an open circuit but all soldered connections are conductive, the gauge may have been damaged during bonding, and, of course, it is useless. If the gauge resistance is different from the manufacturer's specifications, the gauge should be regarded with extreme suspicion, for this, too, indicates probable damage in handling or bonding of the gauge;

(2) Measure the resistance between the strain gauge filament and the structural material with a megohm-meter. The correct reading should be over 10 KΩ;

(3) Gauge bond. Test gauges with Megohmmeter. One pen to structural material. Another to soldering point. Correct reading should be over 50 MΩ. On multimeter at 2 mA, reading should be over 2 μA.

19. Dry the wires with hair dryer.

20. Repeat the above procedures for 2nd, 3rd gauges.

21. Put tapes around the gages.

22. Apply protective coating (M-coat A). Coat the area beneath the naked wire as a layer of insulator.

23. Tape wires. Put wires together.

24. Solder far end of wires so all the leads with each wire stick together.

APPENDIX ITEM # 4

CALIBRATION OF TRANSDUCERS AND REPRODUCIBILITY OF BITE AND EMG MEASUREMENTS

A.4.1. RATIONALE FOR CALIBRATION

Force, like stress, is not a measurable quantity; only the effect of a force producing a strain or displacement can be measured.

Determination of the direction and magnitude of a resultant force acting at a point requires the measurement of strains in three directions on each of three perpendicular planes in 3-dimensional space. The force transducer used in the present study has two parallel (vertical) planes upon each of which a 3-element rectangular strain rosette has been bonded. These two planes are separated by a finite distance. Loads which are applied between the planes cause the planes to bend. The attached strain gauges respond to both axial and bending strains.

The point of applying the load is assumed to have the same effect as that of applying the load through a pair of teeth between which the force transducer is used. This assumption is based upon Saint-Venant's principle (Dally and Riley, 1965). St.-Venant's principle states that at some critical distance away from the application of a load, the resulting stress distribution is unaffected by the manner in which the load is applied. Thus, a distributed load can be represented by a single vector. For the case of the teeth in contact, the contact force can be regarded as a single vector knowing that the stresses applied to the transducer a "distance" away will be unaffected by this simplification of the applied load. In this case the "critical distance away" could be interpreted as the maximum distance between contact points of the bite on the transducer.

There are no available equations in strain and stress analysis for developing a relationship on the basis of the configuration of the force transducer (used in the present study) which aims to determine the direction and magnitude of a resultant force acting mid way between the two vertical planes. In fact, all that can be determined is the direction and magnitude of the resulting force acting in each of the two planes. If the applied force is mid-way between these planes and is parallel to these planes, then the direction and magnitude of the resultant force can be determined and theoretical expressions can be developed which will compute the resultant force and direction based on the strain gauge readings.

Ideally, a force transducer should be equally sensitive to forces in all directions in 3-dimensional space. The design of the force transducer in the present study does not meet this condition. It is more sensitive, *i.e.*, less rigid or more flexible, to forces projected in the sagittal plane than to forces projected in either of the other two perpendicular directions. Thus, a load that is applied at an angle to the two less sensitive planes causes these planes to distort and the strain gauges record bending and axial strains. However "cross-talk", where one plane picks up a portion of the information intended for a different plane, occurs. This drawback is turned into an advantage through an empirical relationship which calibrates the out-of-plane information into a repeatable measurement of forces acting out of the two parallel planes. This occurs because of the inability to eliminate cross-talk and the unequal stiffnesses in 3-perpendicular directions which causes torques to develop.

A.4.2. CALIBRATION OF TRANSDUCERS

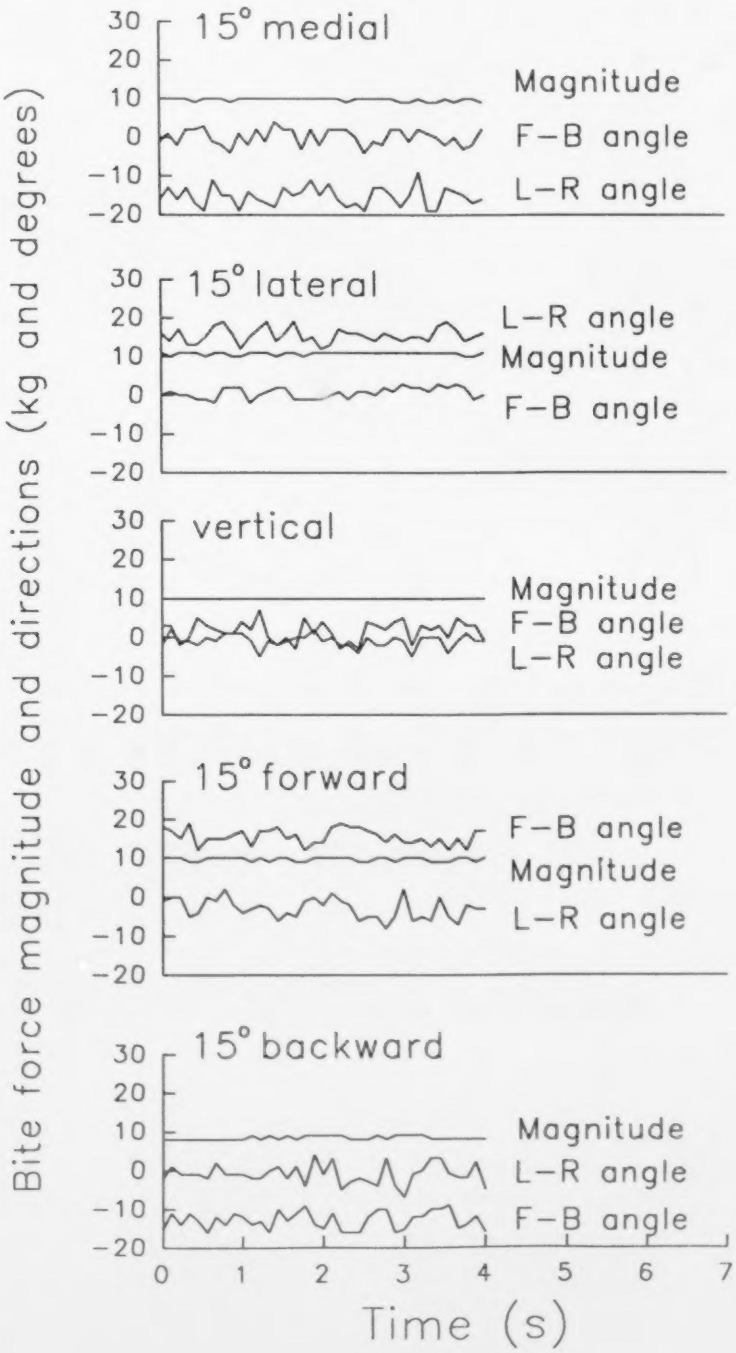
Calibration of the transducer was done by the author's supervisor. Calibration results were entered into the computer program used to predict the magnitude and directions of a bite force. The mathematics and the programming were checked by applying known loads to the transducer and checking that the output displayed on the screen matched the known input. Appendix Figure 1 (*p*. 288) shows the force records for applying 10 *kg* loads in 5 different directions: 20° medial, 20° lateral, vertical, 20° forward, and 20° backward. Both the magnitudes and directions that are measured with the force transducer are close to the real loads and angles. The accuracy of calibration for the force transducers used in the present study is also shown in Table 5 (*p*. 167). The transducer was regularly checked each time before it was used in a subject.

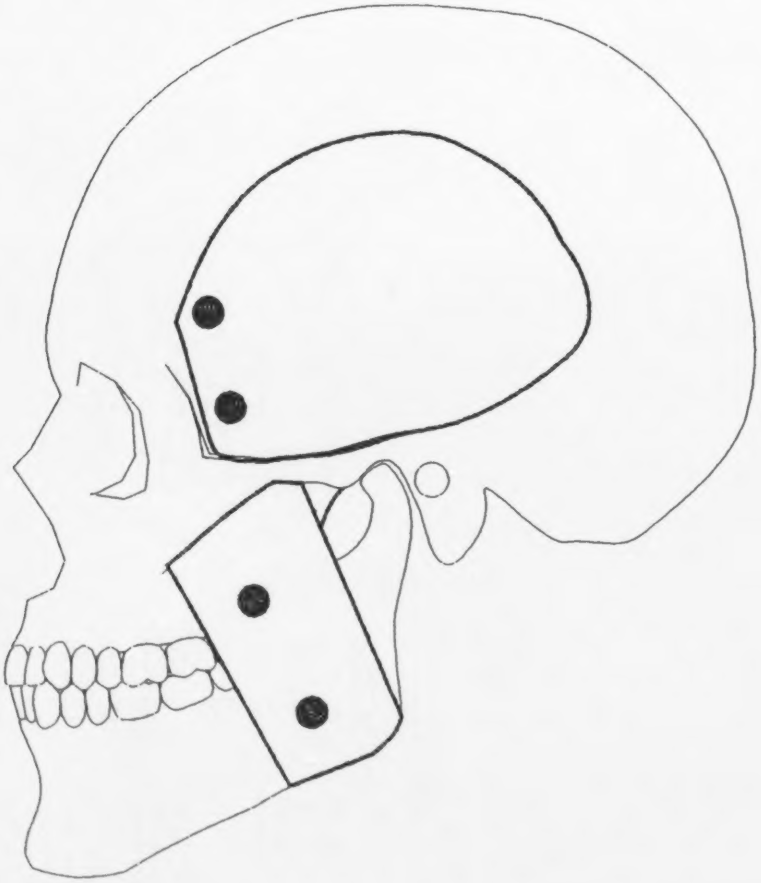
A.4.3. REPRODUCIBILITY OF BITE AND EMG MEASUREMENTS

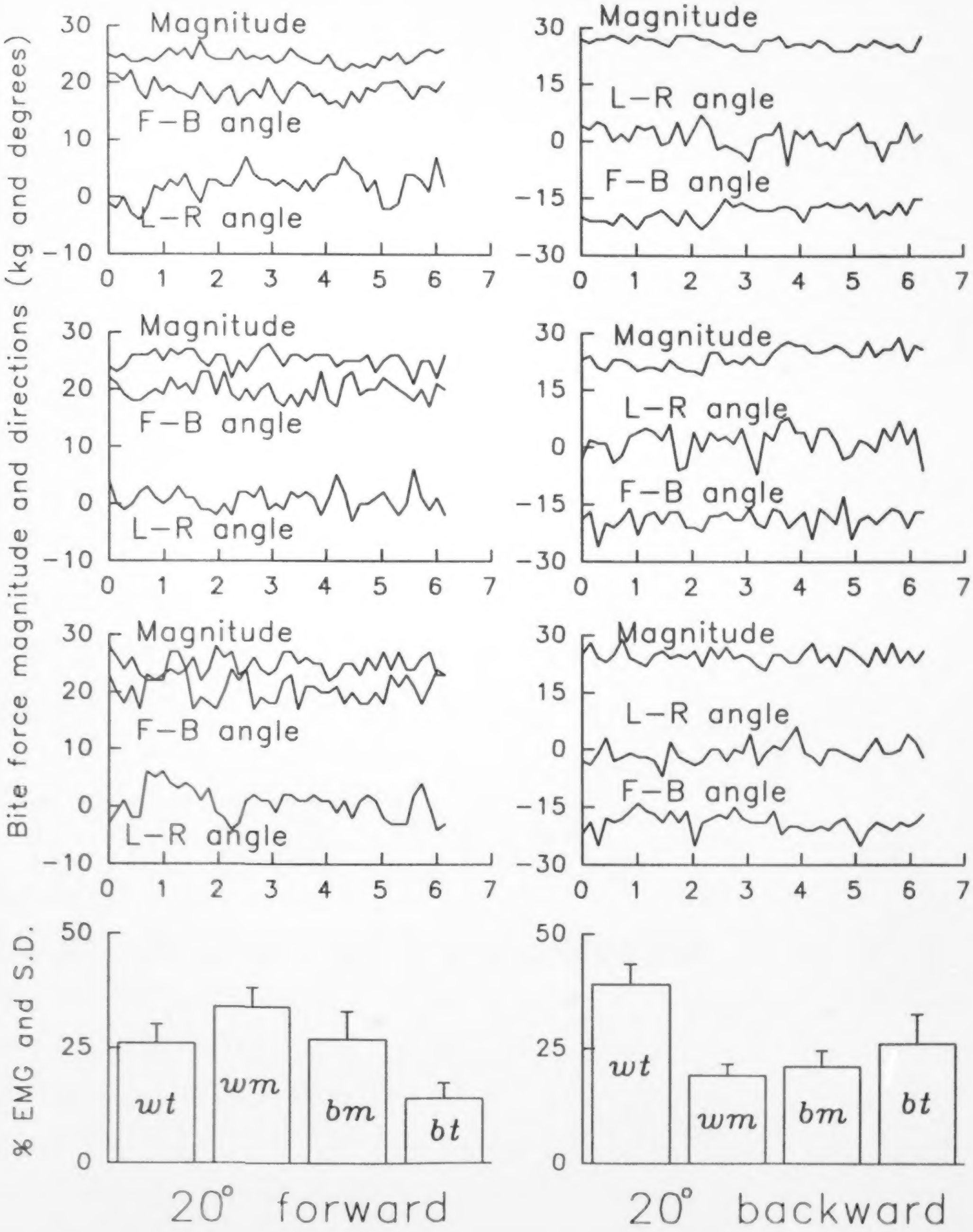
Reproducibility of bite and EMG measurements was tested with three trials on one of the normal subjects participating in the present study. The three trials were carried out in three consecutive days. The position of electrodes was the same as that used for collecting data in the main text of the thesis and was kept constant for different days by marks placed on the skin. The position of electrodes used for superficial masseter and anterior temporalis is shown in Appendix Figure 2 (*p*. 289). All other conditions, such as acrylic blocks for the transducer and instrument setup, were maintained constant. Tasks used for the reproducibility trials were bite forces of 20° forward and 20° backward at 250 *N*. Both the bite force and EMG records were taken. EMG records were acquired and processed in the same fashion as that in the main text of the thesis (3.II.2 and 3.II.3).

Appendix Figure 3 (*p*. 290) shows the results of these trials. Plots in the left-side column represent bite force and EMG records for the 20° forward bite forces and those in the right-side column represent those for the 20° backward bite forces. For the convenience of display the unit for bite forces was the kilogram rather than Newtons ($1\ kg \approx 9.81\ N \approx 10\ N$) although strictly kilogram is the unit for mass while Newton is the unit for force. The right side of the jaw was the working side. Therefore, *wt* represents the working (right) temporalis; *wm* represents the working (right) masseter; *bm* represents the balancing (left) masseter; and *bt* represents the balancing (left) temporalis.

It was found that both the directions and magnitude of bite force were reasonably well maintained. For the 20° forward bite force, the standard deviation was 16% of the averaged (over three trials) normalized EMG activity of the working temporalis, 13% of that of the working masseter, 23% of that of the balancing masseter and 24% of that of the balancing temporalis. For the 20° backward bite force, standard deviations was 12% of the averaged (over three trials) normalized EMG activity of the working temporalis, 14% of that of the working masseter, 17% of that of the balancing masseter and 25% of that of the balancing temporalis.


15° medial
Magnitude
F–B angle
L–R angle
15° lateral
L–R angle
Magnitude
F–B angle
vertical
Magnitude
F–B angle
L–R angle
15° forward
F–B angle
Magnitude
L–R angle
15° backward
Magnitude
L–R angle
F–B angle
30
20
10
0
–10
–20
0
1
2
3
4
5
6
7
Time (s)
Bite force magnitude and directions (kg and degrees)




Bite force magnitude and directions (kg and degrees)
Magnitude
F−B angle
L−R angle
30
20
10
0
−10
15
−15
−30
0 1 2 3 4 5 6 7
% EMG and S.D.
50
25
0
wt
wm
bm
bt
20° forward
20° backward

APPENDIX ITEM # 5
CONSENT FORM FOR THE NORMAL SUBJECT

TITLE OF PROJECT

Measurements of electromyographic activity in jaw muscles of subjects producing predefined bite forces in three dimensions.

INVESTIGATORS

Dr. Jeffrey W. Osborn	492-4480	435-5670 (res)
Dr. Jian Mao	492-1340	431-0895 (res)

PURPOSE

We are studying the pattern of muscle activity in people with normal jaws. Later we wish to study muscle activity in people who have symptoms of pain associated with jaw activity. A comparison of the differences may be important in diagnosing and treating some problems associated with painful jaw muscles.

PROCEDURE

1) Surface electrodes are placed over your jaw muscles. They are harmless. All equipment is medically approved and safe for human subjects.

2) An instrument placed between your teeth measures your bite force. You will be able to "see" this recorded on the screen of a computer. You will be asked to bite on the device using a particular force and in a particular direction while we record the activity in your muscles. The experiment is repeated for different bite forces in different directions.

POSSIBLE COMPLICATIONS

All parts of the apparatus are free from potentially harmful electricity. The only possible complication is a sensitivity to the paste put under the electrodes. To avoid this, let us know if you have any previous history of allergies.

You may get tired when trying to do some tasks because some of them are difficult for some subjects. If so, then please stop trying. It is very important that you feel comfortable so that we can be confident that you are behaving as normally as possible.

ACKNOWLEDGEMENT

We greatly appreciate your participation without which this study, which may in the long run be of importance in diagnosing and treating a very common problem, would be impossible.

...2

CONSENT

I acknowledge that the research procedures described on this sheet and of which I have a copy have been fully explained to me, and that any questions that I have, have been answered to my satisfaction. In addition, I know that I may contact either Dr. Osborn or Dr. Mao if I have further questions in the future. I have been assured that personal records relating to this study will be kept confidential.

Signature of subject

Signature of witness if applicable

Signature of investigator

DATE ____________________

APPENDIX ITEM # 6
CONSENT FORM FOR THE TMD SUBJECTS

TITLE OF PROJECT

Identifying the source(s) of muscle pain associated with temporomandibular pain subjects

INVESTIGATORS (alphabetical)

Dr. Paul W. Major	492-7696 (office)	
Dr. Jian Mao	492-1340 (office)	431-0895 (res)
Dr. Jeffrey W. Osborn	492-4480 (office)	435-5670 (res)

Patient Management Assistant: Betty Skrypichayko (492-2300)

PURPOSE

We have studied the pattern of muscle activity in people without jaw muscle pain. Now we want to use those sensitive indicators to identify the source(s) of pain associated with the "so-called" TMJ problem. A comparison of the differences may be important in diagnosing and treating some problems associated with painful jaw muscles.

PROCEDURES

1) Surface electrodes are placed over your jaw muscles. They are harmless.

2) An instrument placed between your teeth measures your bite force. You will be able to "see" this recorded on the screen of a computer (eg., how hard you are biting and what direction of your bite force is). You will be asked to bite on this Hi-Tech device using a particular force and in a particular direction while we record the activity in your muscles for four seconds per task. The experiment is repeated for different bite forces in different directions. It may take one to two hours including resting periods.

POSSIBLE COMPLICATIONS

All parts of the apparatus are free from potentially harmful electricity. The only possible complication is a sensitivity to the paste put under the electrodes. To avoid this, let us know if you have any previous history of allergies.

You may get tired or even painful in your jaw muscles. However, since each recording only takes place for four seconds, temporary pain should not be a serious problem. In any case you feel that you can not continue with an experiment you can always withdraw.

If you have any questions about or problems following the experiment, please do not hesitate to contact any of the above three investigators.

---- continued on Page 2

ACKNOWLEDGEMENT

We greatly appreciate your participation without which this study, which may in the long run be of importance in diagnosing and treating a very common problem, would be impossible.

CONSENT

I acknowledge that the research procedures described on this consent form and of which I have a copy have been fully explained to me, and that any questions that I have, have been answered to my satisfaction. In addition, I know that I may contact Dr. Major, Dr. Mao, or Dr. Osborn if I have further questions in the future. I have been assured that personal records relating to this study will be kept confidential.

Signature of subject

Signature of witness if applicable

Signature of investigator

DATE (print) ________________

APPENDIX ITEM # 7

CLINICAL EXAMINATION FORM

ID Date

Positive: **1**
Negative: **0**

Mandibular Movement

Vertical Movement

☐ Maximum opening (between upper and lower incisors)
____ (normal range: 40 - 60 *mm*)

☐ Passive stretch opening
____ (normal range: 42 - 62 *mm*)

☐ Restriction?

☐ Pain?

☐ Jerky?

☐ **S** deviation? (positive if ≥2 *mm*)

☐ Lateral deviation (positive if ≥ 2 *mm*)

Other Movements

☐ Protrusion
____ (positive if ≤ 7 *mm*)

☐ Pain?

☐ Right Latero-trusion
____ (positive if ≤ 7 *mm*)

☐ Pain?

☐ Left Latero-trusion
____ (positive if ≤ 7 *mm*)

☐ Pain?

☐ **Rigidity of jaw upon manipulation**

ID Date

Positive: **1**
Negative: **0**

TMJ Noise

R	L	
☐	☐	Reciprocal vertical click (Eliminated with ant. repositioning)
☐	☐	Reproducible opening click (not with closing)
☐	☐	Reproducible closing click (not with opening)
☐	☐	Reproducible laterotrusive click
☐	☐	Non-reproducible click (incl. opening/closing/lateral)
☐	☐	Crepitus - fine
☐	☐	Crepitus - coarse
☐	☐	Popping (audible without stethoscope)

Jaw Muscle and TMJ Palpation

Extra-oral muscles

☐	☐	Ant. temporalis
☐	☐	Mid. temporalis
☐	☐	Post. temporalis
☐	☐	Deep masseter
☐	☐	Ant. masseter
☐	☐	Inferior masseter
☐	☐	Digastric, posterior
☐	☐	medial pterygoid, lower
☐	☐	Vertex

TMJ Capsule

☐	☐	Lateral
☐	☐	Posterior
☐	☐	Superior

Neck muscles

☐ ☐ Upper SCM
☐ ☐ Mid. SCM
☐ ☐ Lower SCM
☐ ☐ Trapezius, insertion
☐ ☐ Trapezius, upper
☐ ☐ Splenius capitis

Intra-oral muscles

☐ ☐ Lateral pterygoid
☐ ☐ Medial pterygoid
☐ ☐ Temporalis, insertion